# SURFICIAL PLACER GOLD DEPOSITS

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## ABSTRACT

This review summarises the factors which control the formation and distribution of surficial gold placer deposits. Regional tectonic and climatic conditions as well as gold source are considered.

The characteristics of eluvial, alluvial, marine, glacial and fluvioglacial gold placer deposits are described. Particular attention is paid to the gold grains within these placers. These gold grains have a distinctive morphology and chemical composition which reflect the manner in which they were transported, deposited and concentrated within the placers.

The knowledge of the processes which lead to the formation and location of surficial gold placers is then used to guide exploration and target potential deposits, which can then be evaluated.

# CONTENTS

PAGE

INTRODUCTION

## LIST OF TABLES

**Table No.** Title

## INTRODUCTION

Placer deposits have been exploited by man for more than 6 000 years and probably provided him with the first samples of gold. If the Witwatersrand and other quartz-pebble conglomerates can be regarded as paleoplacers or modified placers, then these deposits have provided more than two-thirds of the total world gold supply. The term "placer" is of Spanish derivation and was used by early Spanish miners in North and South America as a name for gold deposits found in the sands and gravels of streams (Boyle 1979).

Gold placer deposits occur in a wide range of environments throughout the world. The global distribution of principal unconsolidated (nonlithified) auriferous placer districts is shown in Figure 1.

Placer deposits have developed in certain localities during specific periods of earth history (Boyle, 1979; Henley and Adams,1979; Pretorious, 1981; Guilbert and Park, 1986; Minter, 1991; Loen, 1992). This is illustrated by the placer districts of Otago and Westland, New Zealand, California, U.S.A and many others which occur mainly in convergent tectonic settings and in similar sedimentary environments, which are either of late Archean-early Proterozoic or Cenozoic age (Henley and Adams, 1979). Gold placer deposits also occur within distinctive geomorphological domains controlled mainly by climate and tectonic settings (Sutherland,1985).

Climate controls many of the variables that are relevant to placer formation ( e.g. weathering, rate of erosion, nature of sediment supply, opportunities for sediment reworking). Time constraints, size of drainage areas and denudation rates are also of importance in the formation of placers (Loen, 1992).

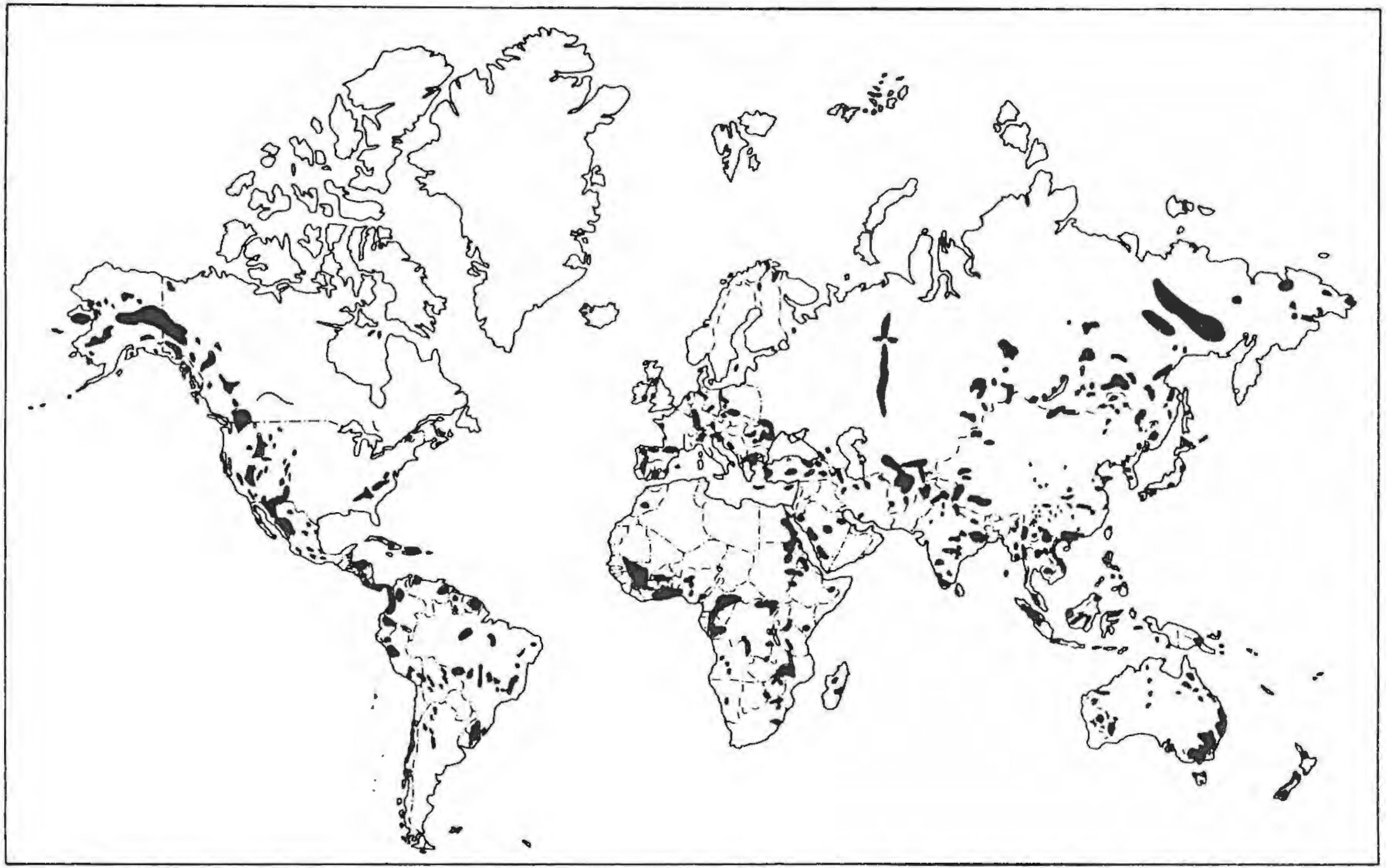


Figure 1. Principal unconsolidated (nonlithified) auriferous placer districts of the world, (after Boyle, 1979).

The distribution of placer deposits is also influenced to a certain extent by the occurrence of primary gold sources (Boyle, 1979).

Gold placers are surficial mineral deposits formed by the mechanical and chemical concentration of gold from weathered detrital or residual material.

Weathering is of prime importance in the formation of gold placers. The gangue minerals in gold-bearing rocks are disintergrated and leached away, causing the gold to migrate slowly downward by gravity or to remain behind as a residual deposit. The gold may remain in situ in the oxidized zones or may pass into eluvial or fluvial placers. The gold in the primary deposit may be dissolved and carried away from the deposit, in which case no placer is formed, or the dissolved gold may be reprecipitated partially or wholly on nuclei of gold in residuum or on similar nuclei in the alluvium of streams, rivers and beaches etc. The formation of placers is a combination of both mechanical and chemical processes which interact over a long period of time.

Gravity, moving water in streams and rivers, wave action along the shores of lakes, seas and oceans, the wind and glacial activity are important (mechanical) agencies which assist in the transport and concentration of gold into eluvial, alluvial, marine, aeolian, and fluvioglacial placers.

Gold placers range in size from individual stream deposits to giant placer goldfields which have yielded over 1500t of gold (Henley and Adams 1979).

The successful location of economic concentrations of placer gold requires an understanding of the controls, on the distribution and formation of gold placers which in turn necessitates the development and use of an exploration model.

Target areas should be investigated using a variety of exploration techniques. These include remote sensing, photogeology, geophysics, geochemistry and biogeochemistry. The evaluation of placer deposits incorporates detailed geological mapping, pitting, trenching, sampling and geostatistics. Bulk samples are taken from pits, trenches and boreholes to determine the gold content of the placer deposits. The grade of the gold-bearing gravels or sands is expressed as the value (in grams, ounces or pennyweights) of gold per tonne, per cubic yard or per cubic meter.

Feasibility studies will take into account the geology, dimensions and grade of the placer deposit, after which a decision can be made as to whether the deposit will be exploited at a profit.

## 1 FACTORS CONTROLLING THE DEVELOPMENT OF PLACERS

### Introduction

The formation and distribution of gold placer deposits is controlled, to a certain extent by tectonic settings, climate and geomorphic conditions, time constraints, size of drainage areas and denudation rates. The occurrence of primary gold sources will in some instances influence placer formation and distribution in that the gold released from primary gold deposits may be concentrated forming residual, lateritic or placer deposits.

## 1.1 Tectonic Control

Some of the most productive gold placers (Table 1) occur in convergent tectonic settings (Henley and Adams, 1979). Their distribution (Figure 2) can be related to specific tectonic and sedimentary environments. The placer districts of Otago and Westland, New Zealand, California, U.S.A, British Columbia, Canada, the Klondike and Yukon Territories and many others lie on the Pacific margins and formed during the Tertiary in similar tectonic and sedimentary environments. In each, the erosion and the reworking of the sediment that formed the placers is related to regional uplift, and the uplift and consequent mountain formation is related, in turn, to changes of relative plate motions in the late Tertiary. Convergent plate boundaries and crustal narrowing in continental areas appear to have provided suitable environments for the formation of gold placer deposits.

## 1.2 Geomorphological Control

The importance of geomorphological controls in the formation and distribution of placer deposits is stressed by Sutherland (1985). Their distribution is largely related to recent variations in geomorphological processes acting at the earth`s surface where a gold source exists. The surface form of the land masses is a product of three variables: namely the nature of the underlying rocks, the structural style as expressed in the tectonic regime and the external processes acting on the surface that are controlled mainly by climate.

The distribution of bedrock sources of gold of Precambrian, Palaeozoic and Mesozoic-Cenozoic sequences as well as the distribution of placer deposits of Tertiary to Recent age are depicted in Figure 3.

Table 1. Giant Placers (after Henley and Adams, 1979).

| Location of gold placer | Date of European discovery | Approximate yield of placer gold, oz x $10^6$ | Ratio of placer : lode gold* | Age of host rocks to parent mineralization |
|---|---|---|---|---|
| Otago, New Zealand | 1861 | 8.0 | 27 | Mesozoic |
| Westland, New Zealand | 1864 | 5.1 | 2.5 | Palaeozoic |
| California, U.S.A. | 1849 | 42† | 2 | Palaeozoic |
| British Columbia, Canada | 1857 | 6.0 | (11) | |
| Klondike, Yukon Territories | 1896 | 9.0 | (9) | Palaeozoic |
| Fairbanks, Alaska, U.S.A. | 1903 | 8.0 | 38.5 | Palaeozoic |
| Lena–Amur region, U.S.S.R. | | 40.0 | – | – |
| South America | | | | |
| Colombia | 1493 | 32 | 2 | Tertiary? |
| Peru | | 4.0 | | Tertiary? |
| Bolivia | | 9.9 | Predominantly placers | Tertiary? |
| Chile | | 11.0 | | Tertiary? |
| Witwatersrand, South Africa | 1886 | 843 | (840) | Archaean |

* The ratio of placer : lode gold was estimated from available data; parentheses indicate relatively trivial recorded lode production from region (data sources, references 3 and 40).

† Yield in ounces estimated on basis of $US 20/oz.

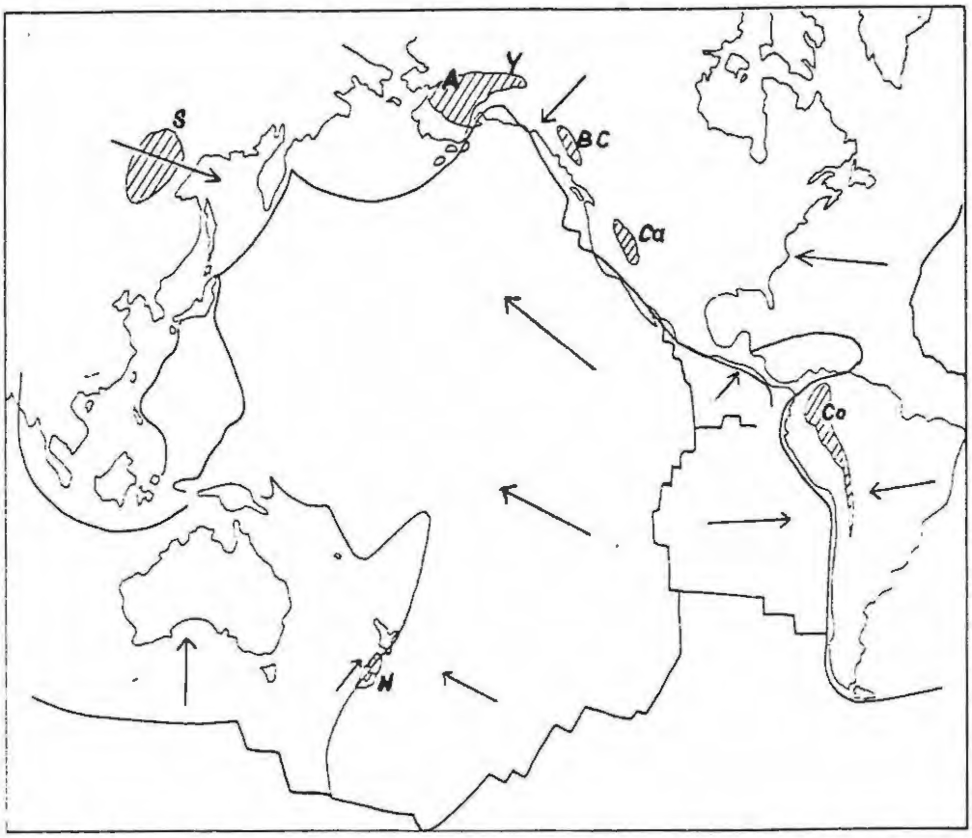


Figure 2. Tectonic structure of circum-Pacific area, showing giant placer regions. A, Alaska; Y, Yukon; BC, British Columbia; Ca, California, Co, South America (Colombia,etc); N, New Zealand (Otago, Westland); S, Russia (Siberia); (after Henley and Adams,1979).

Three principal associations may be observed between sources, tectonic setting and placer development. The first relates to Precambrian shield areas, where variations in gold concentrations on the different shields are related to differing rates of erosion on the uplifted cratons. Similarly, deposition of cover sediments in areas of cratonic downwarp or during periods of marine on-lap will vary from one shield area to the next.

The occurrence of rich gold concentrations in certain shield areas with low rates of erosion and limited fluvial transport can be related to the solution and reprecipitation of gold. The second association is with orogenic belts in which gold mineralization is principally of Palaeozoic age. These areas are typified by the Appalachians, Urals and the Great Dividing Range of Australia. The third gold placer association is with primary sources in Mesozoic and Cenozoic mountain ranges.This association is particularly pronounced around the Pacific Ocean. These areas are characterized by high relief, extensive tectonic and volcanic activity and highlands that are undergoing high rates of erosion juxtaposed with narrow, deep sedimentary basins in which there is extensive sedimentation. However, the high rate of sedimentation is not always favourable for placer development, as the large volume of sediment produced reduces the opportunity for gold concentration. The variability of tectonic movements in both time and space can result in the alternation of periods of rapid sedimentation and periods of lower erosion rates during which sediment is reworked. The opportunity for sediment reworking may also occur in regions where uplift and tilting result in renewed erosion of coarse sediments. These often take the form of very large alluvial fans. Another association occurs between auriferous placers and glaciated coasts e.g. Alaska, West and East Canada, in Chile and New Zealand.

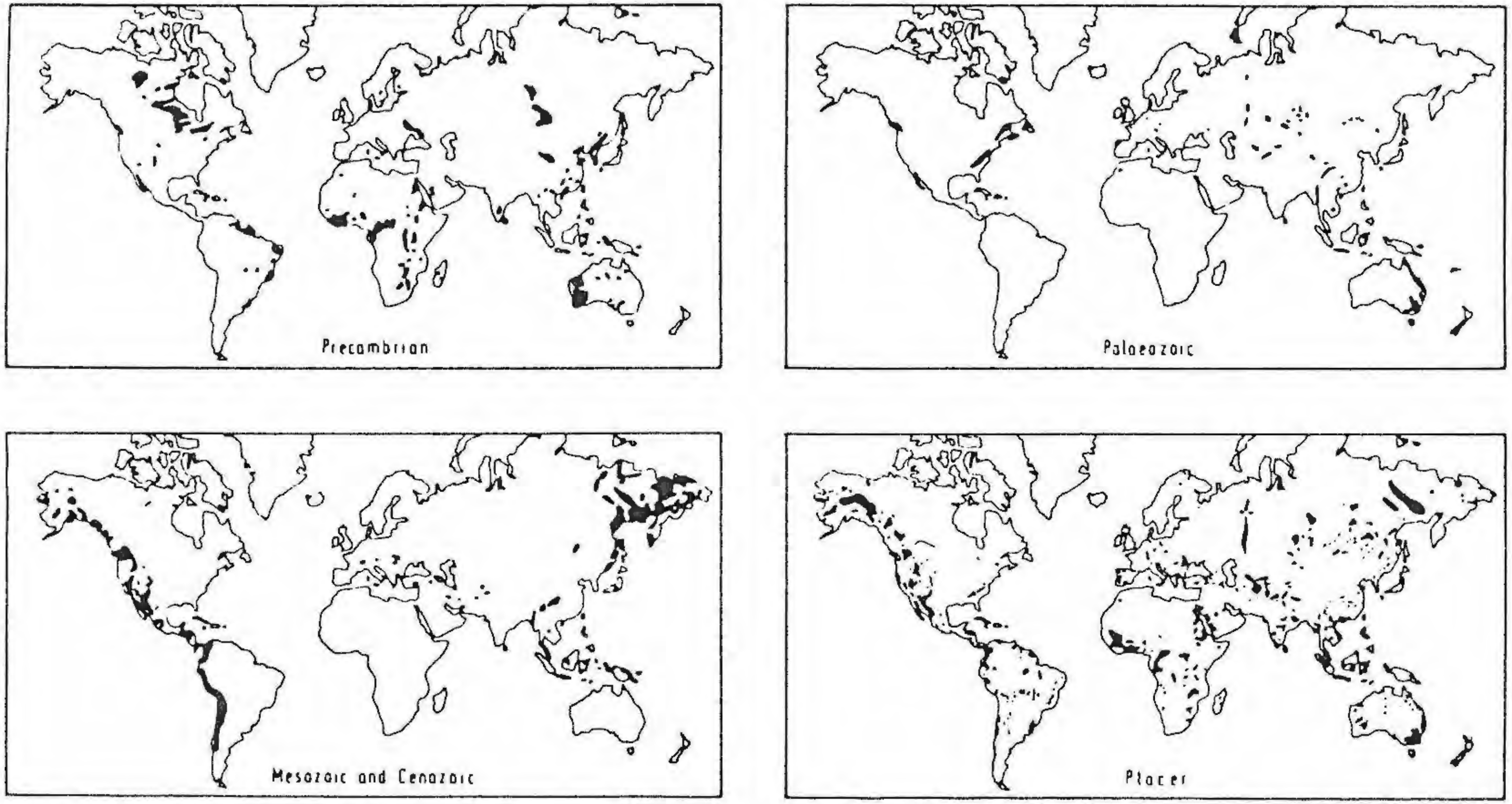


Figure 3. Distribution of primary gold ores of Precambrian, Palaeozoic and Mesozoic-Cenozoic age and of placer deposits derived from these sources (after Sutherland, 1985).

The ores that are primary sources for these deposits have a wide range of ages and the tectonic regimes of the hinterlands vary from cratonic to active orogenic.
In each, the erosion and reworking of the sediment that formed the placers is related to regional uplift. The uplift and consequent mountain formation can be related, in turn , to changes of relative plate motions in the late Tertiary. Convergent plate boundaries and crustal narrowing in continental areas are considered by Henley and Adams (1979) to provide the best environment for giant gold placer formation.

The spatial distribution of placers and many of their characteristics are dependent on various geomorphological processes operating on the surface of the earth and these processes are, in turn, broadly controlled by climate (Sutherland, 1985).

Different types of landform and landforming processes have been grouped into morphoclimatic regions which is useful in understanding placer distribution. However, these landforms can be subjected to more than one set of stable climatic conditions during their existance, and are the product of more than just the simple operation of climatically controlled processes. Consequently, Sutherland (1985) uses the term morphogenetic region. He has identified five such regions (Figure 4):
1) glacial (ice sheet and mountain); 2) cold non-glacial;
3) humid temperate; 4) arid and semi-arid and 5) humid and tropical.

The glacial morphogenetic regions include those areas which are presently glaciated (e,g. Greenland) and those which were extensively and repeatedly glaciated during the Quaternary. The areas are only sporadically underlain by deeply weathered regoliths due to the erosive action of glaciers.

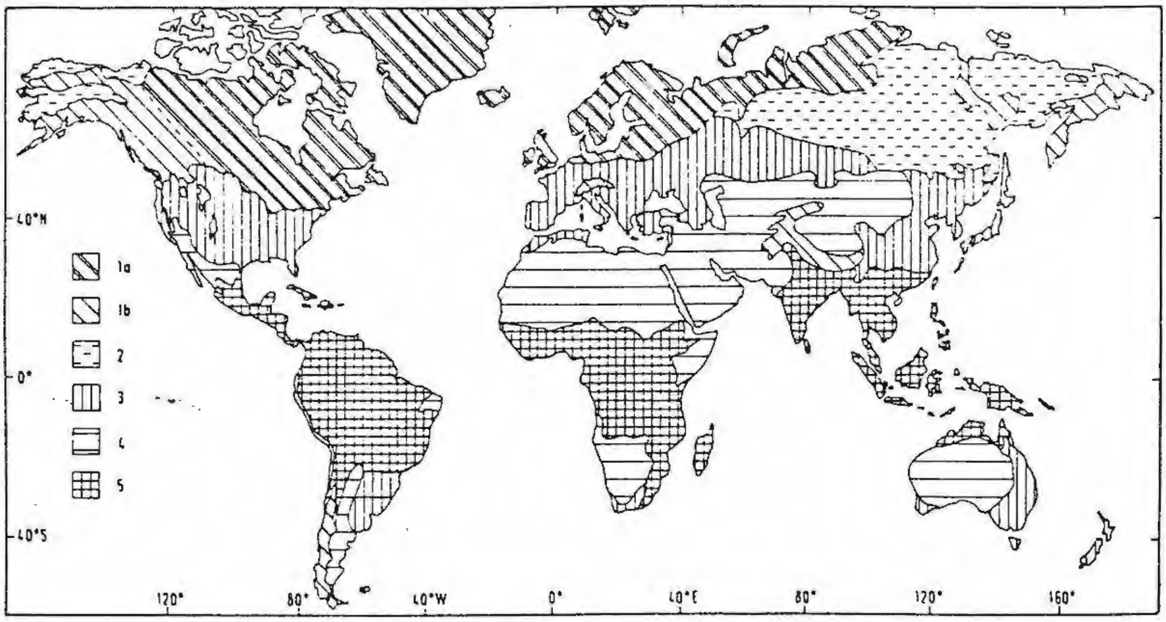


Figure 4. Morphogenetic regions of the world. 1a, glacial regions affected by ice sheets; 1b, glacial regions in mountainous areas; 2, cold non-glacial regions; 3, humid temperate regions; 4, semi-arid to arid regions; 5, humid tropical regions (after Sutherland, 1985).

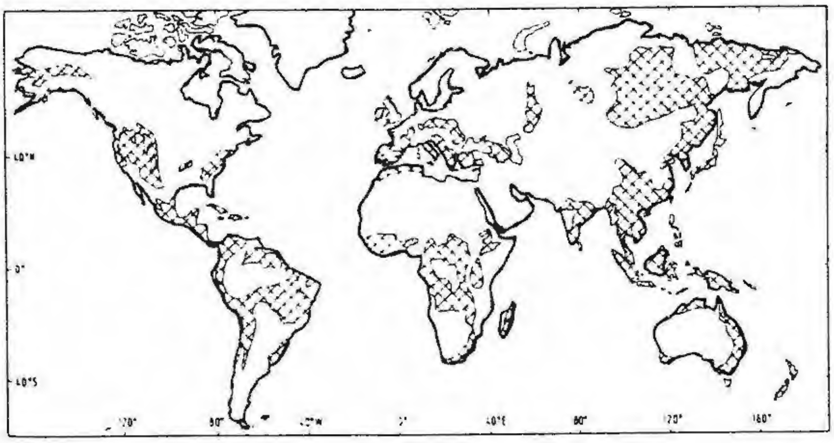


Figure 5. Areas favourable to placer development (after Sutherland, 1985).

Sutherland has subdivided the glacial region into those areas with ice-sheet glaciation and those with mountain glaciation. The former are characterized by very large areas covered with ice resulting in a continuity of landform development over wide areas. In the latter there is considerable topographic control of the ice, which leads to significant discontinuity in landform distribution. Placer deposits in these terraines tend to be infrequent.

The cold non-glacial regions include those areas that are beyond the margins of the Quaternary ice sheets but are presently underlain by continuous or discontinuous permafrost. This incorporates most of Siberia and large parts of Alaska and NW Canada. In this region, a thin active soil layer, limited vegetation cover and seasonal snow melt combine to produce a brief period of highly concentrated fluvial activity in late spring and early summer. This temporal concentration of fluvial activity, together with the contrast in thermal regime between the soil and partially thawed valley bottoms and the frozen interfluves, results in fluvial incision.

Weathering is dominated by mechanical processes and the nature of the regolith is dependent on the character of the bedrock. Silt and clay percentages are generally low and soil processes leave high proportions of material that can only be transported as part of the bedload when they reach the river system. Important to placer formation is the permafrost, which, with it`s seasonal, active layer, prohibits widespread stripping of pre-existing deposits or regoliths inherited from the Tertiary. The Tertiary was a period when the liberation of gold from primary deposits was more effective because of a warmer climate. Rich placer deposits may therefore be formed where the periglacial fluvial system has intersected these earlier sediments.

The humid temperate regions occur mainly in the northern hemisphere with a more restricted distribution in the southern hemisphere. They are characterized by deep weathering profiles in which there is relatively little alteration to clay minerals. River flow is perennial and strongly modulated by vegetation cover. This combination of factors is conducive to placer formation although the arenaceous weathering profiles give rise to large volumes of bedload-sized material that may rapidly dilute placer gold concentrations away from the primary gold source. There is a low overall sediment yield because of the vegetation cover. These areas are not conducive to placer formtion.

The semi-arid to arid morphogenetic region has very high run-off rates which result from irregular but intense rainfall and limited interception by a sparse vegetation cover. Rock weathering is dominated by mechanical breakdown with limited chemical disintergration making large proportions of bedload-calibre material available for transport. The large volume of sediment entrained during fluvial events produces a high density fluid that is capable of transporting heavy particles. Fluvial activity is very effective but its ephemeral nature leads to poorly sorted sediments and limited reworking.

Aeolian processes are also active in this morphogenetic region. The effectiveness of these processes in forming gold placers is generally poor. Most gold placer deposits are largely of a residual or lag nature.

The humid tropical regions are characterized by high temperatures, perennial stream flow and ubiquitous vegetation cover. There is extensive and deep chemical weathering of bedrock that is significant in a) detaching weathering-resistant minerals from surrounding rock,

b) producing a regolith that is dominated by clay-sized particles with only a subsidiary element of coarse sand or larger calibre material that would form bedload in the river system and c) effecting chemical denudation and mass solutional loss reaching 40% of the bedrock prior to any mechanical erosion of the regolith. The combination of this in situ enrichment with the removal in suspension of a large part of the fine particles from the regolith upon mechanical erosion results in favourable conditions for placer development. Much of the humid tropical zone has experienced semi-arid conditions during the Quaternary, and during such periods fluvial activity may have been particularly efficient in eroding the decomposed regolith and transporting the liberated gold particles. The return of humid conditions and increased vegetation cover would reduce sediment supply and encourage reworking of sediment introduced into the fluvial system during arid conditions. A combination of these circumstances could produce large placer deposits.

When considering the formation of placers in the above morphogenetic regions it becomes apparent that climatic change plays an important part in the formation of placers. There have been 23 major changes in climate over the last 100 Ma (Sutherland, 1985). Global changes in climate, and accompanying changes in the surface processes responsible for placer formation during both the Tertiary and, more particularly the Quaternary, have been important in producing the alternation between erosional and depositional conditions that are especially suitable to placer formation. What may seem to be simple placer deposits are likely to be the end product of complex fluvial reworking. Primary source, tectonic setting and morphogenetic processes all interact to allow the identification of regions in which placer formation is favoured (Figure 5 ).

### 1.3 Gold Source

The formation of placers results from the weathering of rocks in an elevated source and the gradual concentration of resistant heavy minerals into an adjacent sedimentary depository (Henley and Adams, 1979; Sutherland, 1985; Force, 1991). Important to the formation of placer deposits is the location and relative gold content of potential source rocks (e.g., Herail et al., 1989: Pearson et al., 1991: Loen, 1992; Figure 6).

A common problem encountered in studies of placers is that the postulated source rocks appear to contain insufficient gold concentrations to account for the amount of gold recovered from the associated sedimentary deposits (Parker, 1974; Boyle, 1979; Robb and Meyer, 1990; Loen, 1992). Loen, (1992) has considered the mass balance constraints on gold placers and has provided possible solutions to source area problems using the following mass balance equation:

$$P= \frac{(D \times Ad \times C \times T \times R)}{100} \times E, \qquad (1)$$

where P = total mass of heavy mineral in placer deposit (t), D = mean density of source rocks ($t/m^3$), $A_d$ = drainage basin area ($km^2$), C = mean abundance of heavy mineral or element in source rocks (ppb), R = mean denudation rate (cm/ka), T = time constraint on erosion of source rocks (Ma), and E = efficiency of weathering and concentration processes (%).

Loen`s mass balance equation is based on the assumption that the mass of a specific mineral (variable P) that accumulates in a placer is limited by the mass of that mineral that can be derived from a given mass of crust (containing mean abundance C) which is weathered or decomposed for a given time interval (variable T). The rate at which source rocks are decomposed conforms to the rate at which the earths surface is lowered by erosion processes, as expressed by denudation rates (variable R), which are fairly well understood for both ancient and modern conditions ( Saunders and Young, 1983; Kukal, 1990; Figure 7). The total mass of source rocks is the product of mean density (variable D) and volume of source rocks. The volume of source rock can be established by multiplying the basin drainage area (variable $A_d$) of streams associated with the placer by the thickness of source rocks that are stripped off (thickness can be determined by multiplying denudation rate [variable R] by time constraints [variable T];Figure 8).

Efficiences of placer-forming systems are commonly low because a substancial proportion of placer minerals is either not released by weathering or is chemically and mechanically lost from the system. Available data (Boyle, 1979) suggest that approximately half of the gold in some gold placer systems is released by weathering, although other research (Yeend, 1974: Henley and Adams, 1979) suggests lower levels of efficiency. Using the mass balance equation (1) and an efficiency (E) of between 10 and 50 percent Loen (1992) constructed Table 2 for several Cenozoic gold placers and the Witwatersrand. The reliability of the results shown in Table 2 are dependant upon the precision of constraints on values for mass balance variables, which vary depending on the amount of geological and geomorphic data that are available.

The placer mass balance model provides specific explanations for the varying productivity of placers of differing age and setting. The model stresses that the volume of source rocks eroded (Figure 9) is the dominant control on the amount of gold that can potentially be deposited in sediments. The volume of source rocks eroded is the product of time span T, denudation rate R, and drainage basin area $A_d$.

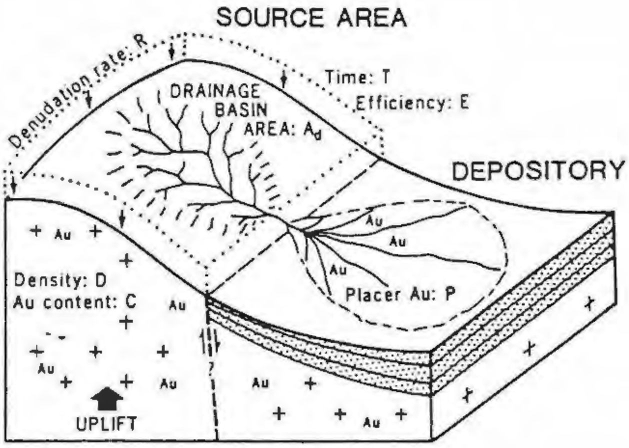


Figure 6. Schematic diagram illustrating constraints on formation of placer deposits. Variables in equation (1) are shown in relation to geomorphic attributes. 'Au' indicates gold concentrations. The normal fault along the edge of the basin is not present in all districts, (after Loen, 1992).

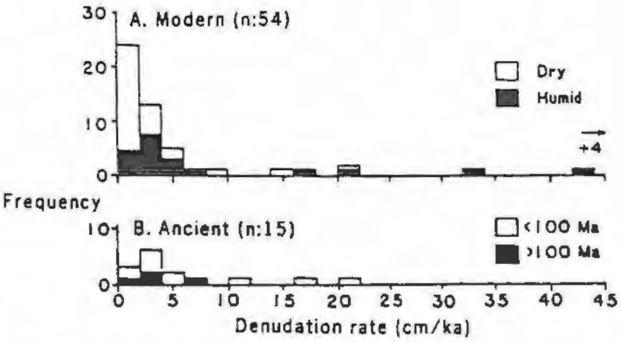


Figure 7. Denudation rates for modern (A) and ancient (B) conditions. Modern rates (A) are rather similar for both wet and dry climates although extreme values are associated with areas having high relief. In contrast, ancient rates (B) are, determined in part, by the length of time span considered; long time spans (>100Ma) are associated with relatively slow rates (<7.5cm/ka) because a larger number of tectonically quiescent periods are included, (after Loen, 1992).

Table 2. Calculations of Mass Balance Characteristics for Cenozoic Gold PLacers and Witwatersrand Deposits (after Loen, 1992).

| Location (age; type) | Mass balance variable calculated | Mass balance variables | | | | | Thickness of source rocks removed (km) | Volume of source rocks (km$^3$) |
|---|---|---|---|---|---|---|---|---|
| | | P (tons Au) | $A_d$ (km$^2$) | R (cm/ka) | T (Ma) | C (ppb Au) | | |
| Witwatersrand, South Africa (Archean; fan, braid delta) | C | 80,000–100,000 | — | — | 126[1] | 0.43–6.80 | — | 55,800–139,500 |
| Sierra Nevada, California (Eocene-Quaternary; stream channel) | C | 1,959–2,177 | 6,000–15,000 | 2–5 | 20–28 | 0.07–3.40 | 0.4–1.4 | 2,400–21,000 |
| Fairbanks, Alaska (Pliocene-Quaternary; stream channel) | P | 238[2] | | | | | | |
| | a. District | 242–2,423[3] | 515 | 10–50 | 5 | 7.1[4] | 0.50–2.5 | 258–1,288 |
| | b. Ft. Knox stock | 53–267[3] | 0.21 | — | — | 1,400[5] | 0.600 | 0.144 |
| Alder Gulch, Montana (Quaternary or older; stream channel) | C | | | | | | | |
| | a. T = 2 Ma | 77 | 100–120 | 5–10 | 2 | 2.42–29.10 | 0.10–0.20 | 10–24 |
| | b. T = 15 Ma | 77 | 100–120 | 2–5 | 15 | 0.65–9.69 | 0.30–0.75 | 30–90 |
| Pioneer, Montana (Miocene-Quaternary; fan, pediment, fluvioglacial) | C | 9.3–13.0 | 50 | 5–10 | 10–12 | 0.12–1.96 | 0.50–1.20 | 25–60 |
| Tarryall, Colorado (Quaternary; fluvioglacial) | C | | | | | | | |
| | a. District | 5.7–6.8 | 60 | 50–500 | 0.500 | 0.03–1.74 | 0.25–2.50 | 15–150 |
| | b. Montgomery ery Gulch stock | 5.7–6.8 | 17.25 | 50–500 | 0.500 | 0.10–6.04 | 0.25–2.50 | 4.3–43.1 |

[1] Robb and Meyer (1991, p. 90); for comparative purposes only, value not used in mass balance calculation

[2] Recorded production for district (7.65 million oz; Nokelberg et al., 1987, p. 78)

[3] Calculated value

[4] Average gold value for greenschist metapelites (Crocket, 1991, table 1.4)

[5] Based on 0.04 oz Au/ton (Hollister, 1991, p. 405)

See text for explanation of choices for values; ranges are used where data are imprecise; dashes indicate values were not used in mass balance calculations (see text); for all examples, D = 2.65 t/m$^3$, and E = 10 to 50 percent

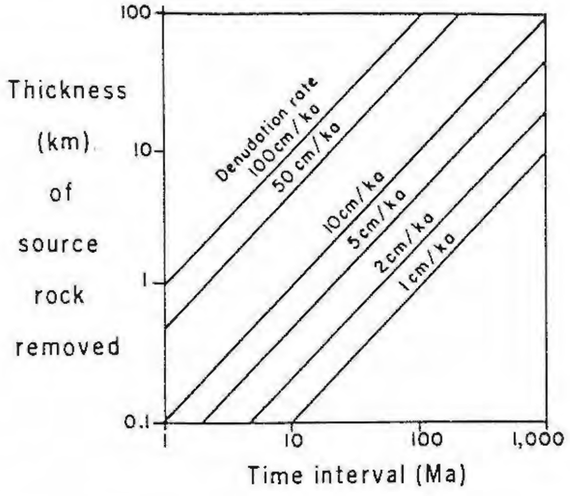


Figure 8. Thickness of source rocks removed in relation to time span for a range of potential denudation rates (after Loen, 1992).

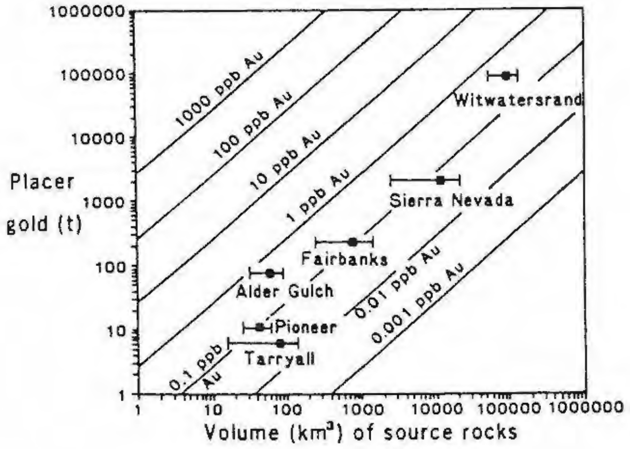


Figure 9. Amount of gold derived from source rocks for Cenozoic placers and Witwatersrand deposits. Estimated ranges of volumes of source rocks and position of average value (squares) are shown. Diagonal lines indicate mean gold content of source rocks. Note that values for the studied deposits plot between 0,01 to 1,0ppb Au (values are not adjusted for efficiency), (after Loen 1992).

Large amounts of gold are available to placers associated with large drainage basins that are eroded for long periods of time at relatively high denudation rates. High denudation rates may result in placer concentrations being transported away from sites of deposition. Long time spans and large drainage basins favour gold concentration (Loen, 1992).

Another important control on gold concentration is the efficiency with which gold is released from the source rock. Placer gold concentrations will not form if the gold is retained in source rock particles, or is chemically or physically removed from the system (Boyle, 1979). Gold cannot be effectively weathered from source rocks if high denudation rates (8-10 m/ka) exist. The aggradational loads of rivers draining such areas will also inhibit sorting processes. Loen`s mass balance characteristics suggest that in many instances (Figure 9; Table 2) gold appears to have been derived from large volumes of source rock containing rather minor concentrations of gold (<10ppb Au; Table 2).

The mass balance model fails to take into account the precipitation of authigenic gold onto detrital gold grains (Giusti,1986; Clough and Craw, 1989; Groen et al., 1990; Craw, 1992; Craw and MacKenzie, 1992; Youngson and Craw, 1993). The estimation of time spans in multicyclic placers is also difficult. The model also assumes static geomorphic conditions throughout the period of gold concentration which is unlikely (Sutherland,1985). The variables $A_d$ (drainage basin area), denudation rate (R) and efficiency E, are loosely constrained as little data exist for them.

## 2 GOLD PLACERS

### 2.1 Classification

Gold placers are surficial mineral deposits formed by the chemical and mechanical concentration of minerals from weathered debris by gravity, water, ice and wind. Gold placers have been classified in a number of ways based upon their genesis or location.

Hails (1976) classified placers according to their genesis:

1) eluvial (slope)
2) alluvial (stream) which includes river-terraces
3) marine (off-shore)
4) beach;
5) residual
6) fossil.

Boyle (1979) grouped placers into two main catagories, namely :

1) Eluvial and residual placers where the placers have formed by the concentration of gold in situ over or in the immediate vicinity of primary deposits, and
2) Alluvial, beach and eolian placers where gold has been concentrated by agencies in the near vicinity or at some distance from the primary source.

Kazakevitch (1972) devised the following genetic placer classification:

| | |
|---|---|
| 1) Eluvial | a. Zones of weathering of gold-quartz deposits |
| | b. Zones of oxidation of auriferous sulphide deposits |
| 2) Slope | a. Solifluction and landslide placers |
| | b. Solifluction and deluvial placers |
| | c. Deluvial and landslide placers |
| 3) Watercourse | a. Alluvial placers |
| | b. Proluvial placers |
| | c. Lacustrine placers |

| | |
|---|---|
| 4) Glacial | a. Placers of main and lateral moraines |
| | b. Placers related to interglacial and glacial streams and other water courses of glacial origin |
| 5) Eolian | Placers in eolian sands |
| 6) Marine | a. Beach placers |
| | b. Placers on underwater slopes |
| | c. Placers in near shore still water (swamps, lagoons, coves) |

Placers covered by younger material have been called buried placers, which if subsequently lithified, are then named fossil placers.

## 2.2 Eluvial Placers

Eluvial placers are generally formed in the weathered material over or adjacent to primary gold deposits (Figure 10). They occur on slopes, downhill from the outcrop of the primary deposit, which has been broken up by weathering and moved downhill by gravity, sheet-wash or soil creep or by a combination of these agencies. The principal mechanism for the concentration of heavy minerals in eluvial placers is the winnowing action of gravity and downhill soil creep, the latter being dependent on the angle of slope or gradient where the placers are formed on the sides of hills or mountains. Secondary factors include the thickness of the slope materials (scree, talus, residuum), the size and specific gravity of the weathered particles in the residuum, the coefficient of friction, the movement of ice and snow (glaciers) and the annual and daily variation of temperature (Boyle, 1979). Continuous downhill creep appears to be the main mechanism by which the gold is transported downslope into fluvial systems in regions of high topography.

Eluvial placers comprise three main classes, namely; 1) residual placers which are formed directly above and coincide with the primary deposit, 2) deluvial ( scree or talus) placers which occur close to the primary deposit and extend down to the base of the slope, and 3) proluvial placers which form in the disintergrated debris at the foot of hills or mountains (Figure 10). Eluvial placers are often closely related to alluvial placers and will often grade into the latter downslope and into residual placers upslope.

The composition of the eluvium is often highly variable and is influenced by the nature of the underlying bedrock, weathering rates, slope gradients, climate and water table levels in the case of lateritic deposits (Le Count Evans, 1981; Webster and Mann, 1984). Eluvium developed over schists is generally composed of a mixture of sand, clay, limonite and disintegrated schist, while in granitic terrains the eluvium is comprised of limonitic clay and disintergrated quartz and feldspar. The eluvium is gossanous when developed over sulphide-rich stockworks or massive sulphides.

Eluvial gold placers have been exploited in many parts of the world. In the United States eluvial deposits have been exploited in California, Oregon, Nevada, Montana and Georgia (Pardee and Park, 1948; Lesure, 1971) and in Brazil in the Minas Gerais and Carajas region of Brazil (Gair, 1962; Dorr, 1969; Andrade et al., 1991). Eluvial deposits have been mined in Western Australia in the Pilbara, Kimberly, Coolgardie, Kalgoorlie and other Yilgarn fields (Webster and Mann, 1984 ; Mann and Webster, 1990). Several economically viable eluvial gold deposits occur in the Clutha-Kawerau region of Central Otago, New Zealand (Henley and Adams, 1979; Craw and Youngson, 1993; Figure 11). The Otago gold placers have produced over 22 680 kgs of gold since they were discovered in 1861.

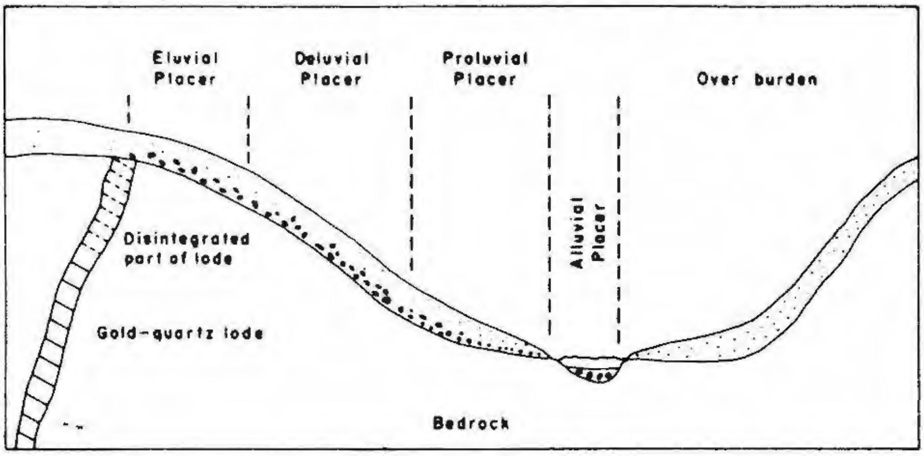


Figure 10. Cross-section of gold-quartz vein supplying material to form eluvial and alluvial placer deposits (after Boyle, 1979).

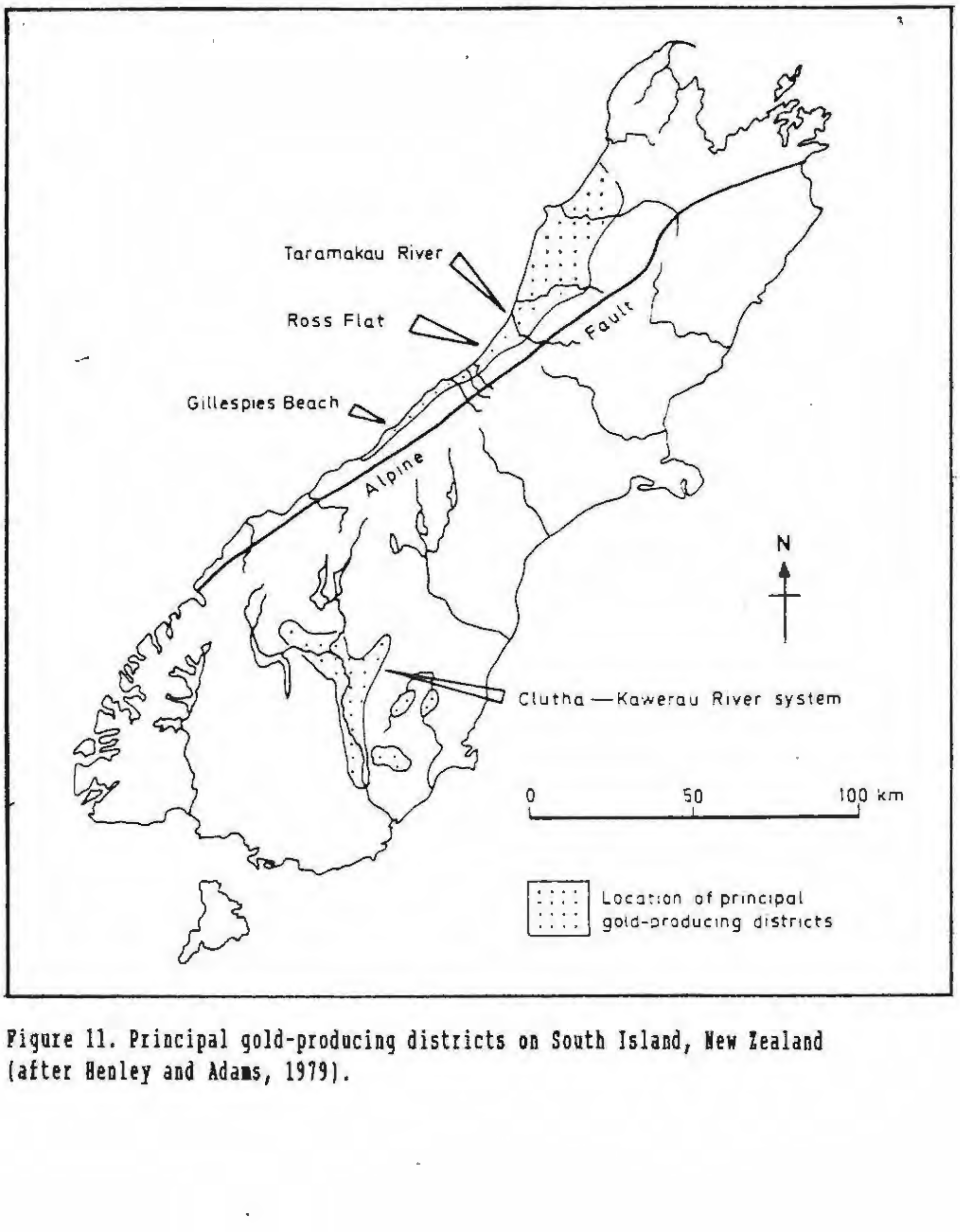


Figure 11. Principal gold-producing districts on South Island, New Zealand (after Henley and Adams, 1979).

The Central Otago region is underlain by highly deformed predominantly greenschist facies schists and greywackes. Uplift and erosion of the schist belt resulted in the development of a regional low-relief surface upon which Miocene fluvio-lacustrine sediments were deposited. Some of the quartz rich gravels which occur in these sediments are auriferous.

The Alpine Fault which marks the Australian/Pacific plate boundary passes through southern New Zealand. Movement along the Alpine Fault has resulted in regional uplift, folding and faulting. The eluvial gold deposits formed, and are still forming on these actively rising mountain ranges. The sediments deposited on the slopes of these mountain ranges consist of sequences of poorly sorted gravel and sand. Many of the gravel units are matrix supported with angular schist clasts floating in a matrix of sand, silt, and kaolinite clay. The sediments are typical mass flow deposits which have accumulated as a series of sheet-like layers (Figure 12). Some units are channelised accumulations of weakly stratified, clast supported, imbricated gravels, with coarse clast supported lag gravels at their bases. The lag deposits occur locally at the bedrock interface at the base of channels and in scours cut into mass flow deposits. The lag gravels have a matrix of sand, silt and mud (Craw and Youngson, 1993).

The gold occurs principally as local concentrations in channel lag deposits. Minor, but locally rich concentrations of gold occur irregularly in the soil and in unchannelised hollows and basins. The gold is commonly highly irregular in shape, coarse (up to 2cm), and is thought to have a substantial authigenic component. The source of the eluvial gold is thought to be from primary gold-bearing quartz veins and from the near surface regions of primary gold deposits where supergene processes have caused gold mobility and reprecipitation. Another source of gold

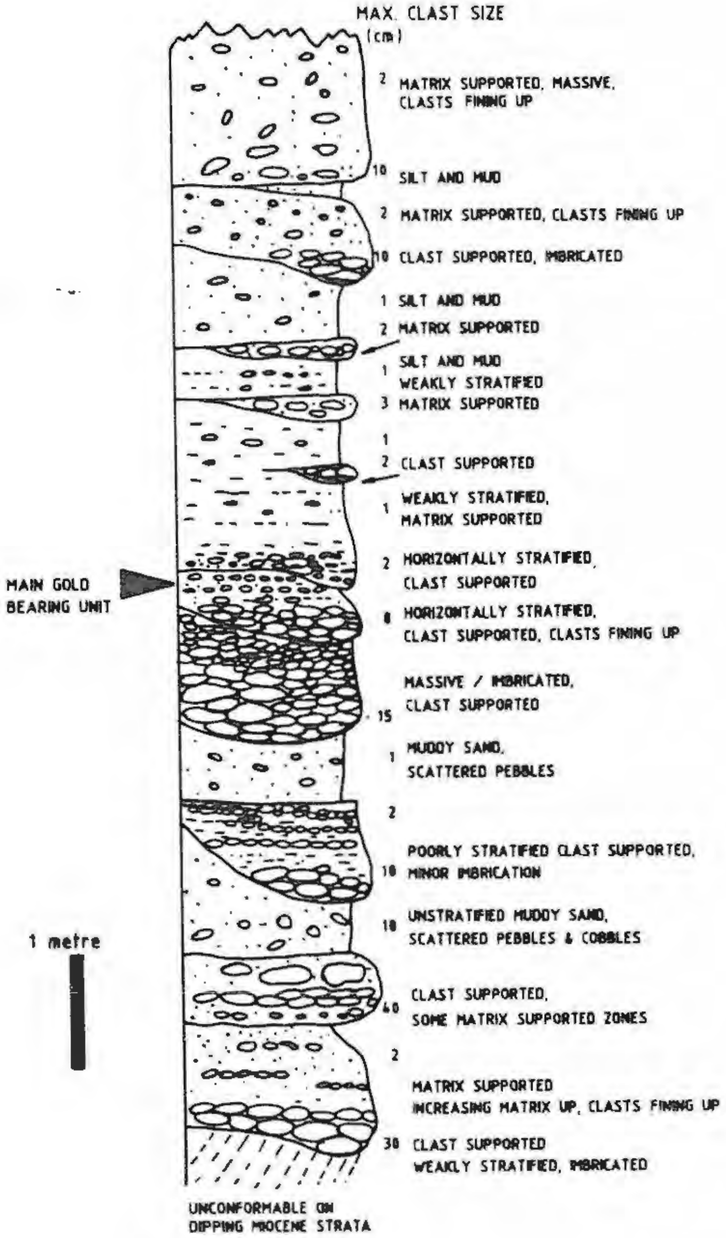


Figure 12. Section through proximal alluvial fan sediments in a complex fan sequence in the northeastern Clutha region (after Craw and Youngson,1993).

is detrital gold in the Manuherikia Group fluvial sediments which overlie the basement schists.

The topographic slopes on the rising mountain ranges show an evolutionary trend in space and time, from gentle, weakly dissected surfaces, through slightly degraded but convex slopes, to deeply incised convex streams. Eluvial gold occurs sporadically on the gentle slopes, with the greatest concentrations where steeper convex slopes have produced an apron of fan sediments. Gold concentration at these sites is seen to have resulted from selective and localized winnowing of the schist material, leaving coarse lag gravels and gold. The coarse grained gold is retained in the eluvial systems while the fine grained gold is released to the alluvial systems downstream.

The morphology, mineralogy and behaviour of gold grains in eluvial gold placers have been studied in detail by Boyle (1979), Santosh et al.(1992), Craw and MacKenzie (1992), and Craw and Youngson (1993).

The gold in eluvial placers tends to accumulate in an irregular manner close to the gold source. Eluvial placers generally contain a wide range of gold grain sizes including coarse irregular nuggety grains, and may occur in tectonic sediments and glacial deposits which are commonly associated with the tectonic sediments (Henley and Adams, 1979; Eyles and Kocsis, 1989).

The rich eluvial deposits in Central Otago, New Zealand, which are young and actively forming, provide some insight into the morphology and processes which govern the nature of the gold. Craw and Youngson (1993) have studied the eluvial processes in the tectonically active areas of Central Otago and have concluded that the eluvial processes are spatially transient. Uplift may cause erosion of early-formed eluvial deposits, while the new eluvial deposits are formed nearby. If erosion rates exceed rates of eluvial formation, the record of the eluvial environment is removed.

Craw and Youngson (1993) have identified two main sources of gold for the Central Otago eluvial placers. Fine grained gold (1-100 microns) occurs associated with sulphides in primary veins which crop out in basement schists. Supergene processes in the near-surface region (<20m) have caused gold mobility in solution followed by reprecipitation onto some of the fine grained particles resulting in an increase in grain size. Resultant gold grains are highly irregular in shape and up to 2cm in width. Once released into the soil the grains are modified by further chemical mobilization and precipitation of gold, and by physical modifications during down-slope creep. This results in the formation of irregular nuggets with rounded extremities. The other source of gold identified by Craw and Youngson (1993) in the Central Otago eluvial deposits is detrital gold from fluvial sediments which overlie the basement. The gold is generally fine grained (100-500 microns), and concentrated in coarse gravel facies. Chemical gold mobility has occurred within these fluvial sediments during uplift (Craw, 1992), and in tectonic sediments after uplift and recycling, resulting in grain size increase (Clough and Craw, 1989; Youngson and Craw, 1993)

The authigenic gold grains are generally >500 microns across and numerous grains are >1 mm, while larger nuggets are rarer but still occur throughout the placers. The morphology of the coarser gold grains indicate that authigenic gold precipitation has taken place. Many of the grains are highly irregular in shape with numerous delicate protrusions which would not have survived fluvial transport.Crystals in the form of skeletal octohedra, and colloidal encrustations are also present. Nuggets partially or wholly enclose mineral grains and authigenic clay minerals (Youngson and Craw, 1993). Some of the coarser grains have one or more recognizable relic detrital cores (Craw, 1992; Youngson and Craw, 1993). The grain size increase due to authigenic growth has also occurred in soils in areas with little erosion, and in repeatedly recycled proximal fan sediments during recent uplift.

Santosh et al.(1992) have studied the morphological and chemical evolution of gold grains associated with primary, supergene and secondary gold deposits which occur in the Nilambur Valley, Wynad Gold Field, of southern India. They have identified processes whereby gold in primary veins is mobilized, chemically purified, and reconcentrated in laterite profiles, effecting enhanced purity and grain growth before transfer to fluvial systems where further refinement takes place resulting in the formation of highly pure placer gold.

## 2.3 Alluvial Placers

Alluvial gold placers are those which formed by the action of moving water, either in streams, rivers, flood plains or deltas. Reworking of these deposits together with others formed as a result of sedimentation or glacial processes may result in the formation of off-shore marine and beach placers. Alluvial placers also occur in mangrove swamps and other areas (Bensusan, 1942) where water movement is limited.

Boyle (1979) has grouped alluvial placers according to their geological location and tectonic history (Table 3).

Table 3. Classification of alluvial placers according to their geological location and tectonic history (after Boyle, 1979).

| Present form | Elevated equivalents | Depressed equivalents |
|---|---|---|
| 1.Gulch, canyon and creek gravels | High level gulch and creek gravels | Deeply burried gulch and creek gravels |
| 2.River and bar gravels | Bench gravels<br>High level river and bar gravels | Deeply burried river and bar gravels |
| 3.River flood-plain gravels | High level flood-plain gravels | Depressed(deeply burried) flood plain gravels |
| 4.Deltaic gravels | Elevated deltaic gravels | Depressed deltaic gravels |
| 5.Beach and shore line gravels | Elevated beach and shore line gravels | Depressed beach and shore line gravels |

Alluvial placers consist of loose unconsolidated clays, siltstones, sands and gravels. In some instances the alluvial material may be coated or cemented with limonite or other precipitates. The cemented alluvial placers often occur where the primary deposit and wall-rock are rich in pyrite, siderite, chlorite and other iron- and manganese-bearing minerals. The majority of alluvial placers in streams and rivers lack persistent and regular bedding or stratification. Pseudobedding, laminations, current or false beds may occur in some alluvial deposits, however bedding and stratification are often well developed in deltaic placers.

In fluvial systems gold may be transported as chemical complexes (Boyle, 1979; Groen, 1990) or as detrital grains carried on the surface of the water, in continuous suspension, in traction or intermittently in suspension and traction. The deposition and concentration of gold in placers involves interactions among the fluid, sediment bed, and transported particles. Physical processes responsible for the concentration of heavy minerals are described by Kolesov (1974), Slingerland (1977, 1984), Komar and Wang (1984), Reid and Fostick (1985), Best and Brayshaw (1985), Slingerland and Smith, (1986), and Kuhnle and Southard (1988).

The formation of water-laid gold placer deposits is strongly dependant on the efficiency of mechanisms which separate dense sediment grains from light grains. Within a fluvial system heavy minerals may be concentrated by hydraulic sorting mechanisms and sediment entrainment processes. The concentration of gold by hydraulic processes in fluvial systems takes place primarily because of density contrasts with lighter silicates which make up a large proportion of a sediment. Sorting of heterogeneous (in size and density) water-borne sediments may be carried out by an alternation of several processes which include; 1) hydraulic sorting (settling equivalence, entrainment equivalence, dispersive equivalence), 2) interstice entrapment, 3) flow separation, (Slingerland and Smith, 1986; Reid and Frostick, 1985; Best and Brayshaw, 1985).

### 2.3.1 Ravine and Creek Placers

Ravine and creek placers occur within the immature reaches of rivers and streams. They occur in regions that have high relief and have undergone extensive weathering and denudation. The gradients within the fluvial systems are moderate. The primary source of the gold is close by, at the head of the water course or along the valley sides. The alluvium comprises components of the surrounding country rock and is coarse in nature. The gold is generally concentrated on the bedrock or in the top few feet of the bedrock. False bottoms may occur but these are very rare. The overburden covering the gold concentrations is not excessive and the gold grades can be extremely rich with the gold occurring within well defined and regular pay streaks. The gold is generally coarse with a high fineness. Large nuggets, wires and crystals are common in these placers, as is the occurrence of vein quartz and sulphide clasts, with veinlets or disseminations of primary gold.

Ravine (gulch) and creek placers are common in the Yukon of northwestern Canada. Detailed descriptions of many of these deposits are given by Boyle and Gleeson (1972), Boyle (1979) and Debicki (1983). Boyle (1979) gives a detailed description of two of these placers, the Dublin Gulch and Haggart Creek placers which occur in the Yukon and serve as typical examples of creek placers.

The Dublin Gulch and Haggart Creek placers (Figure 13) were discovered and worked in 1898. The topography of the area is characterized by low rounded hills, with numerous streamlets occurring in the valleys, which reflect a deeply dissected upland. The bedrock comprises quartzite, phyllite, graphitic schist, limestone and quartz-mica schist. All of the Yukon Group which has been folded and faulted and intruded by granite and granodiorite. Gold-bearing quartz-arsenopyrite-pyrite-sulphosalt veins occur in the underlying bedrock. Within the quartz veins the primary gold occurs mainly as submicroscopic to microscopic particles in the arsenopyrite, pyrite and sulphosalts. The grade of the primary gold within the quartz veins ranges between 5,7 and 42,5 g/t. The country rock and quartz veins are deeply weathered, the latter down to 6m. The gold in the oxidized zone occurs as fine dust, small flakes and abundant wires. Some of the gold (fineness 850) is chemically bound or adsorbed onto limonite and scorodite which occurs in the oxidized zone.

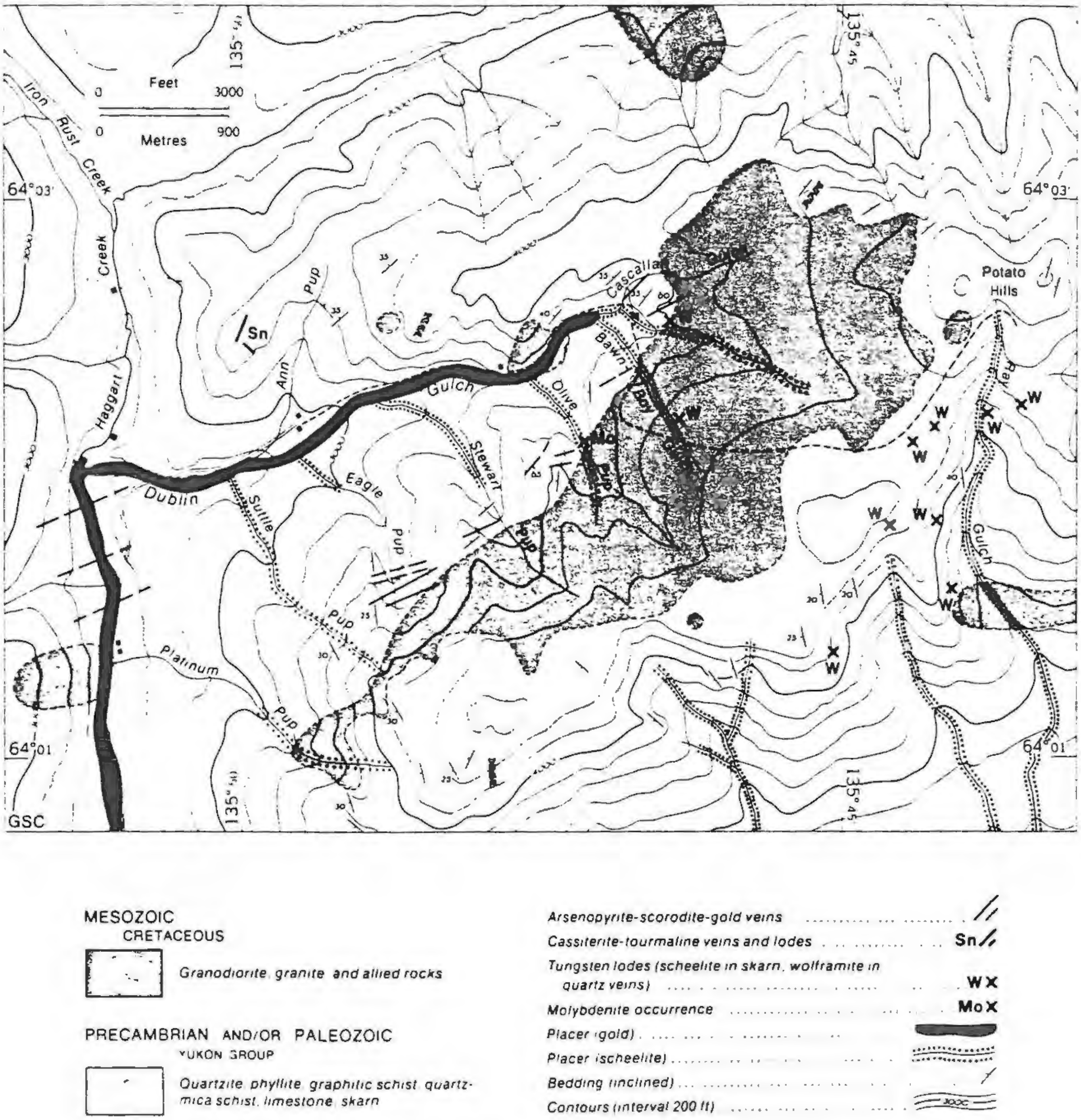


Figure 13. Generalized geology of Dublin Gulch area, Yukon, showing gold placers (after Boyle, 1979).

The streams in Dublin Gulch and Haggart Creek have entrenched parts of their courses in deep overburden, forming terraces with old modified profiles. A 1,5-2,5 m accumulation of gravels, schist fragments, soil and granite boulders, which are probably a product of soil creep and slope wash, occur at the surface. Below this there is a 0,6-0,9 m bluish clay unit, which overlies 1-1,2 m of yellow limonite coated gravels and weathered debris, which represent the product of deep secular weathering of the bedrock and placers during a period of uplift in late Tertiary times.

Gold is reported to occur in these surface materials where they have been washed by streams in the creeks. However, most of the gold occurs on the bedrock in the bottom 0,5 m of the gravels and weathered debris. The pay zone was about 30 m wide at the mouth of the Dublin Gulch, and narrowed upstream. The grade of the ore zone was roughly 0,9 g/t Au cubic metre. The gold is present as fine dust, scales, rough wires and sprigs, occasional crystals, and small nuggets ranging in size from 5mm to 20mm. The nuggets are worn and pitted. The average fineness of the gold is about 900. Free gold in quartz or sulphide clasts has not been reported in this area, however angular fragments of arsenopyrite have been observed in some gold nuggets. The gold is accompanied by wolframite, cassiterite, magnetite, hematite, arsenopyrite, jamesonite, bismuth, galenobismutite, pyrite, tourmaline and garnet. The Dublin Gulch and Haggart Creek placers provide a good example of where gold can be traced from its primary source to the stream placer.

#### 2.3.1.2 Stream and River Placers

Stream and river placers have many features in common with ravine and creek placers. The majority occur in regions with subdued topography marked by broad, terraced, entrenched valleys developed in a terrain of rounded and deeply weathered hills. The present and past gradients of the water courses are moderate to low. The concentrations of gold are not as high as the ravine and creek placers, but the gold mineralization is more regular and extensive. Multiple pay streaks occur at the same elevations or they may be stacked at different levels. The majority of high grade bodies occur on the bedrock which may be due to periods of flooding (Cheney and Patton, 1967) or extensive down-cutting by the river (Tuck,1968) or through subsidence of gold grains (Minter and Toens, 1970; Kolesov, 1974; Shilo and Shumilov, 1976). The gold is finer grained and has a higher fineness than the gold in the ravine and creek deposits. Large nuggets are relatively rare in the stream and river placers. In contrast to the ravine and creek placers the stream and river placers have an overburden of ten to hundreds of meters thick.

Well known stream and river placer districts include the Klondike of Yukon Canada, the Sierra Nevada of California, the deposits of Victoria, Australia and the Lena and Aldan placers of Siberia. The river and stream placers of the Klondike serve as a prime example of this type of placer. Gleeson (1970), Hester, 1970, Boyle (1979) and Debicki (1983) give comprehensive descriptions of the Klondike placers.

The Klondike placer deposits (Figure 14) were first discovered and mined in 1896 and are reported to have yielded in excess of 283 000 kg of gold. The Hunker, Bonanza, Dominion, Gold Run, Sulphur and Quartz Creek placers were the most productive. The bedrock in the Klondike area is mainly Klondike Schist which is comprised of folded and faulted quartz-mica schists, chlorite schists, sericite schists, quartzites, phyllites, pyritic graphitic schists and highly sheared quartz porphyry sills or

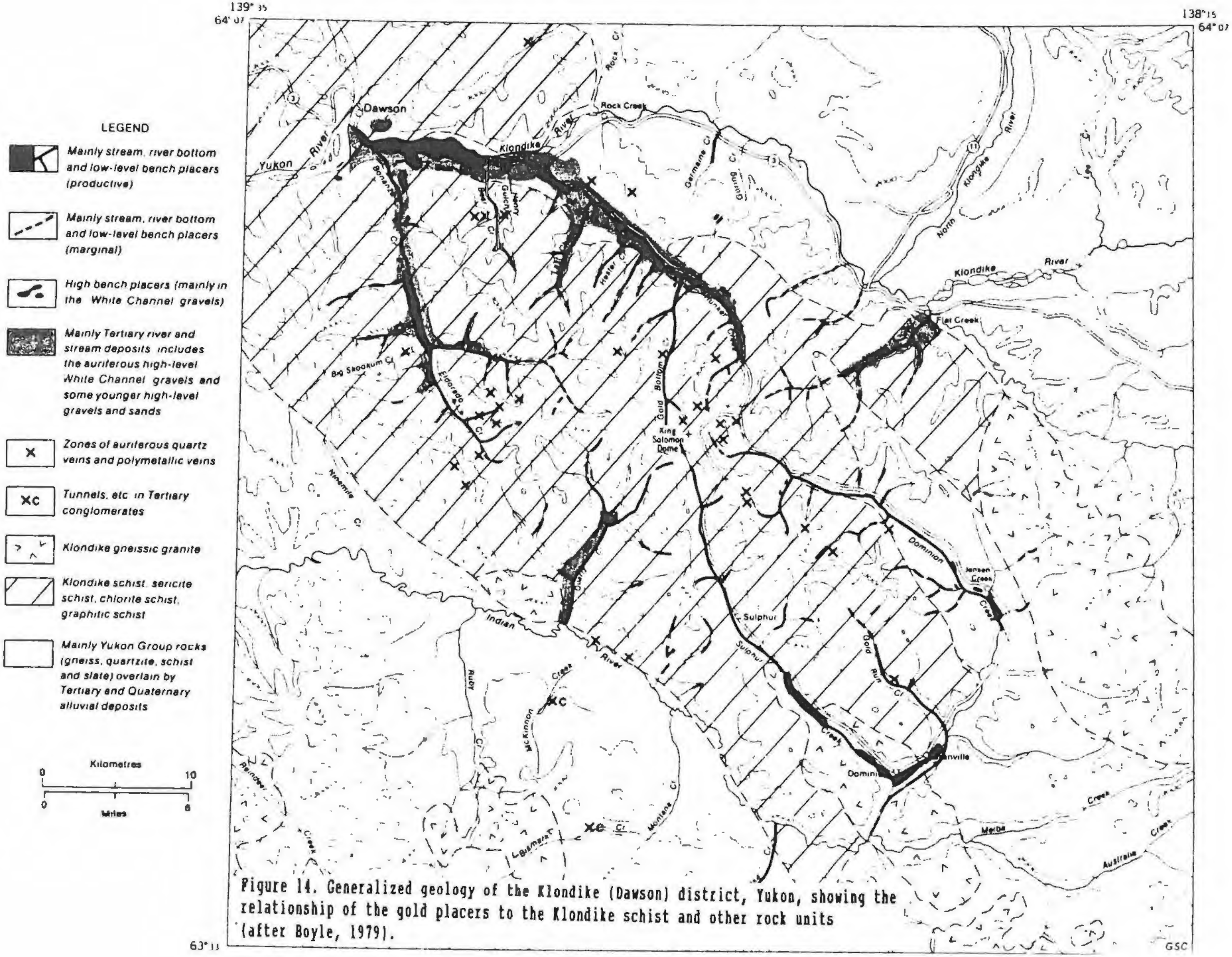


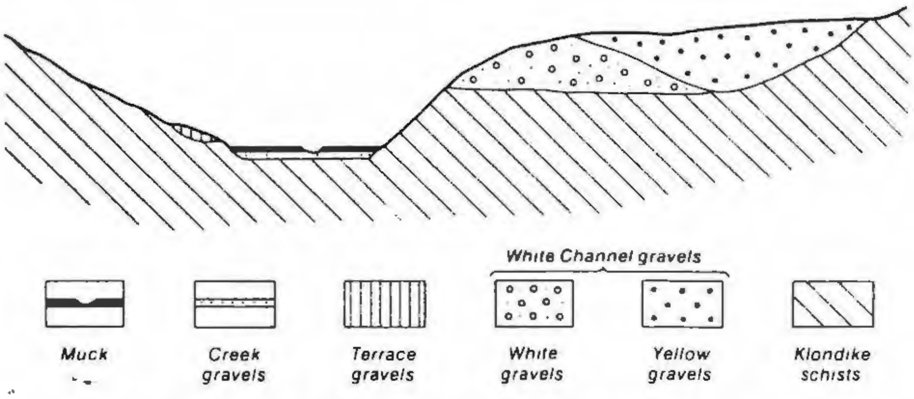
Figure 14. Generalized geology of the Klondike (Dawson) district, Yukon, showing the relationship of the gold placers to the Klondike schist and other rock units (after Boyle, 1979).

flows which are interlayered with the metasediments. The Klondike Schists contain numerous primary quartz bodies, most of which are gold-bearing with grades ranging from 0,28 to 1,42 g/t. The gold occurs in both the native state and in close association with various minerals which include pyrite, galena, barite and sphalerite.

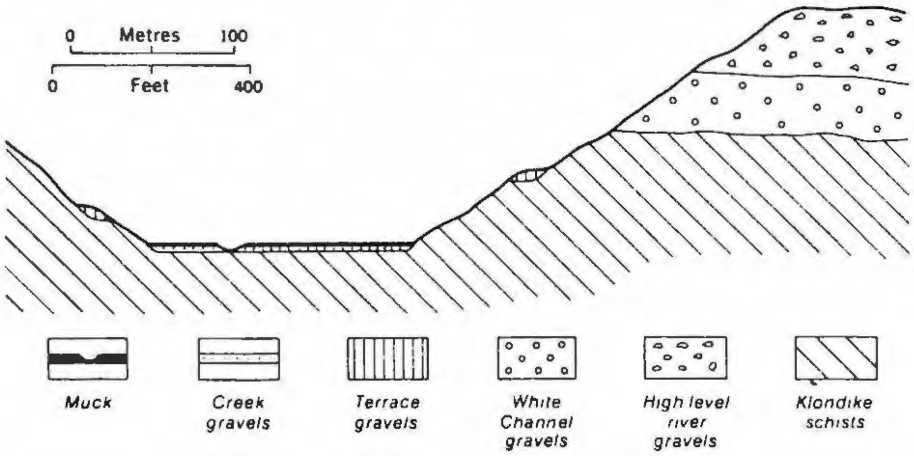
The Klondike district forms part of the Yukon Plateau, which has been intensely dissected. It has rounded hills and numerous small streams which coalesce to form major water courses. The small streams form in large amphitheaters, which run down into steep sided narrow ravines and valleys, which flatten and widen out downstream. The lower slopes of the valleys are terraced with permafrost developed to depths of 60 m in places.

Boyle (1979) concluded that the placers developed as a result of general uplift during the Tertiary, followed by deep secular weathering of the bedrock and quartz vein bodies. V-shaped valleys developed, which gradually widened and filled with extensive gravel deposits. Subsequent uplift resulted in the streams and rivers cutting down to bedrock in places, leaving terraces behind in the process. Several generations of placers have been identified. The stratigraphic relationships between the gravels are shown in Figure 15. McConnell (1905) classified the Klondike placers into three main categories, these include;

- 1.High level gravels:
  - 1.1.River gravels
  - 1.2.White Channel gravels: Yellow gravels
    - : White gravels
- 2.Gravels at intermediate levels: 2.1 Terrace gravels
- 3.Low level gravels:
  - 3.1.Gulch gravels
  - 3.2.Creek gravels
  - 3.3.River and stream gravels



Section across Bonanza Creek valley below Eldorado Forks



Section across the lower part of Bonanza Creek valley

Figure 15. Generalized sections across the placer deposits of Bonanza Creek, Klondike (Dawson) district, Yukon (after Boyle, 1979).

The low level creek gravels occur at the base of all the valleys in the region, and range in thickness from 1,2 to 3 m. They rest on bedrock, which consists of decomposed and broken schists, and are overlain by wind-blown silt and decayed organic matter referred to as 'black muck'. The gravels consist mainly of schist fragments, with minor fragments of other rock types, which outcrop along the valley sides. The schist fragments are flat and disc-like with rounded edges. They vary in thickness from 25 to 50 mm and are 50 to 150 mm in length. Subangular and rounded clasts of quartz and volcanic rock occur in minor quantities in the gravels. The clasts within the low level creek gravels are loosely stratified, and are generally embedded in a matrix of coarse reddish sand and alternate in places with thin layers of sand and decayed organic matter. The low level gulch gravels occupy the upper portions of the main creek valleys and small tributary valleys. They differ from the creek gravels in that they are coarser and more angular. They consist mainly of unworn schist material, which has been washed down from adjacent slopes, and as a result, do not contain any significant concentrations of gold.

The low level river gravels consist of quartzite, slate, chert, granite and diabase clasts , transported over a large distance. They are the only low level gravels which appear to contain economic concentrations of gold, which is as a result of reworking and concentration of gold within the gravels. The intermediate level terrace gravels lie on rock terraces that occur at various points cut into the steep slopes of the present valleys. The terraces are remnants of former valley bottoms formed during the deepening of the valleys. These gravels are generally less than a few meters thick and 100 m in length and have an irregular distribution with thicknesses ranging from 1,8 to 4,6 m. They are often covered by layers of decayed organic material.

The high level gravels are extensively distributed along the creeks and represent ancient creek deposits, overlain by gravels from the Klondike River when it ran at a much higher level than at present, and occupied a much wider valley. The high level river gravels rest on high level creek gravels at an elevation of roughly 140 m above the present valley bottoms. They range in thickness from 45 to 53 m and are comprised of well rounded pebbles of quartzite, slate, chert, granite, diabase and conglomerate contained in a matrix of grey sand. The gold content of the high level river gravels is minimal and generally of little economic significance.

The high level creek gravels, which are also referred to as White Channel gravels, represent ancient creek deposits laid down in the wide, flat bottomed valleys. They were characteristic of the region before the last period of general uplift. Subsequent to the deposition of the creek gravels the landscape was elevated over 180 m. This enabled the water courses to incise down through the sediments, to the bedrock beneath and to excavate the steep- sided valleys in which they now run. The White Channel gravels now occur on wide benches bordering the present valleys at elevations of 45 to 90 m above them. The elevation of the gravels generally increases downstream. Their distribution along the valleys is irregular, due to the erosion of a large portion of the gravels during the deepening of the valleys following the last uplift.

The White Channel gravels consist of a compact matrix of small, clear, little worn, and often sharply angular grains of quartz and platelets of sericite, closely packed with rounded and subangular, wedge-shaped quartz boulders 0,6 to 0,9 m in diameter. Subangular clasts of sericite schist are also present in minor quantities in the gravels. The deposits are nearly always stratified and white in appearance. The white colour is due to the abundance of quartz and the leaching of a large proportion of the iron originally contained in the rock. The gravels vary in thickness from a meter to over 45 m and in width from 30 m to over 1 km. The gravels increase in volume downstream and are best developed at the mouths of the streams and rivers. Rusty coloured gravels, which are loosely bedded and contain less quartz, are sometimes developed at the margins of the White Channel gravels. These generally represent flood plain deposits, which seldom contain economic concentrations of gold.

The White Channel gravels are interpreted as having been deposited by widening streams with easy grades and relatively slack currents. The preponderance of quartz clasts gives them the character of a residual deposit (Boyle, 1979).

The White Channel gravels have large accumulations of gold. This is primarily due to the long time period which enabled large quantities of primary gold to be released by weathering and concentrated in the water courses. The highest concentrations of gold in the White Channel gravels occur within the first meter, above the bedrock or in the top 0,5 m of the bedrock. False bottoms are rare (Boyle, 1979). The nature of the bedrock appears to influence the degree to which the gold is concentrated. When the bedrock is compact the gold is concentrated towards the base as opposed to when it is loose which results in the gold being dispersed throughout the gravels in contact with the bedrock. The majority of the placer deposits mined in the Klondike district appear to have been very persistant in length and width and sometimes contained rich concentrations of gold. A low level creek gravel of the Eldorado Creek yielded more than 0,5 kg Au per meter over 6 km.

The gold occurring in the river and stream placers is highly variable in both fineness, shape and size. Near the heads of the water courses the gold occurs as coarse angular grains, flakes, sprigs and wires and as nuggets. In a downstream direction the gold grains become more rounded, flattened and finer grained with the nuggets decreasing in size. The gold in the White Channel gravels ranges from fine grained to coarse, rough flakes and particles. Nuggets are common but not very large. In the high and low level gravels the gold generally has a crystallized character and sometimes completely encloses grains of quartz, which are often identical to the quartz found in the local primary gold deposits (Boyle, 1979). Dendritic gold has also been observed on pebbles within the placers. The fineness of the Klondike gold is highly variable, within and between individual water courses. The fineness of the gold ranges from 625 to 890. This may be related to the original differences in the grade of the primary quartz vein gold.

The origin of the gold in the Klondike placers has long been debated. There are no known primary deposits associated with the placer deposits large enough to have supplied all the gold in the placer deposits. McConnell (1907) and Boyle (1979) believe that there is sufficient evidence to support the theory that the gold in the Klondike placers was derived from the Klondike Schists. The mass balance model proposed by Loen (1992) supports McConnell and Boyle`s belief and could account for the concentrations of gold in the placers. Evans (1981) suggests that the concentration of gold occurred as a result of the chemical deposition of secondary gold. Girling et al (1979) suggest that biogenic activity could have played a part in the concentration of gold in the Klondike placers.

The morphology, mineralogy and behaviour of gold from fluvial placers has been studied extensively ( Tourtelot and Riley, 1971; Viljoen, 1971; Boyle and Gleeson, 1972; Yeend, 1975; Boyle,1979; Hallbauer and Utter, 1977; Giusti and Smith, 1984; Giusti, 1986; Berrange, 1987; Bowles, 1988; Clough and Craw, 1989; Groen et al. 1990; Craw, 1992; Santosh et al. 1992; Minter et al. 1992).

Giusti (1986) describes the shape, size and behaviour of placer gold grains from stream sediments of the North Saskatchewan River and Athabasca River of Alberta. Two major morphological varieties of gold were observed: 1) flaky, scaly gold, with folded and hammered edges, with crystals or crystal faces still visible on grain surfaces; and 2) so-called sandwiched, droplike particles, sometimes toroidal. Both varieties were found to be coated with authigenic gold. Some of the grains collected by Giusti measured 2 to 2.5 mm, while the the majority of gold grains studied varied between 0.500 and 0.010,mm with a large fraction smaller than 0.063 mm. During sluicing and panning operations fine grained gold was often observed floating on the wash water. The gold grains from the North Saskatchewan River were found to be relatively coarser than those recovered from the Athabasca River.

The long axis (L), the breadth (B), and the thickness (T) of each grain collected was measured in order to obtain the Corey shape factor, $T/\sqrt{LB}$ for each gold grain examined. The Corey shape factor was used to describe the flattening of the gold grains. Small Corey shape factors are indicative of highly flattened grains, while large values indicate that the particles are nearly spherical. The smaller the Corey shape factor, the more readily the grains are transported by stream currents (Giusti, 1986). The average Corey shape factor (X) was found to be higher for the Athabasca River gold ($X = 0.3$) than that for the North Saskatchewan River particles (X = 0.176).

The gold grains showed increasing flattening for a decreasing size of gold grain. The fine gold was transported faster than the coarser gold with the majority of gold grains being moved along the river beds by rolling. Many spherical gold particles were observed in the sediments of the Athabasca River and are probably a product of frequent rolling and collision. Giusti (1986) found that most of the gold particles from both drainage systems were flakey in shape, with folded edges (Figure 16A-B); some were toroidal (Figure 16F). Many of the smallest gold particles were repeatedly bent and droplike in shape (Figure 16C-E) with the result that their Corey shape factors became quite high. A lower degree of maturity was found for the gold from the Athabasca River, which was related to the more complex drainage history of the river, to the pronounced influence of glaciation, and to the mixing of different types of gold grains.

Gold grains from placer deposits may have high-purity gold rims. It has been postulated that the rim is produced by the leaching of the silver from the grain boundary (Desborough 1970; Grant et al.1991) or that it is formed by the addition of pure gold to the outer part of a grain of different composition. The formation of gold-rich rims on gold grains in placers has been investigated by Giusti and Smith (1984); Giusti (1986); Bowles (1988); Clough and Craw (1989); Groen et al.(1990); Santosh et al. (1992); and Craw and Youngson (1993).

Giusti (1986) often observed gold crystals or crystal faces and skeletons (Figure 17A-D) in the placers of Alberta. He concluded that they were of three major types: 1) primary, often hidden in folded portions of the grain; 2) secondary, related to plastic deformation and internal recrystalization;

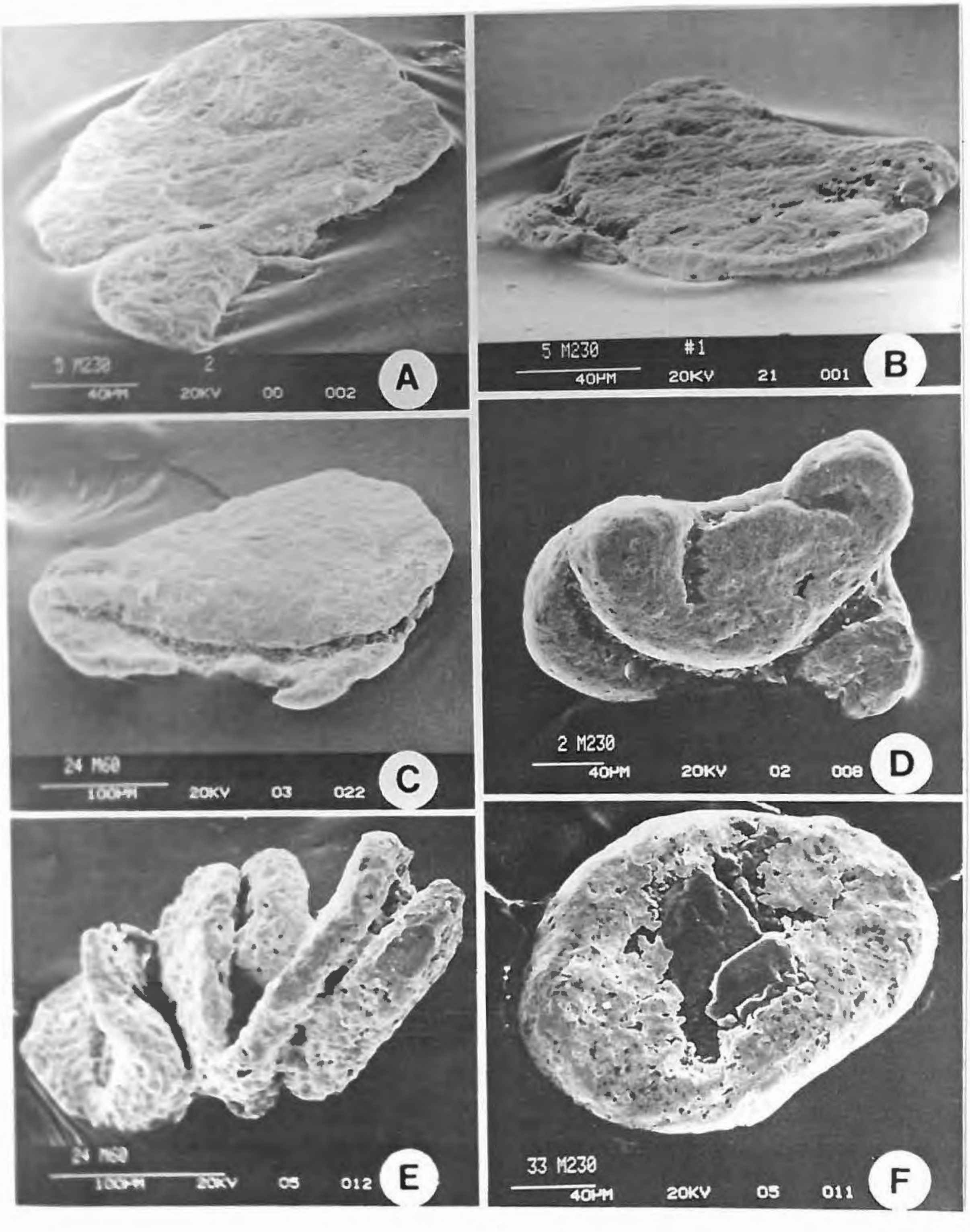


Figure 16. Scanning electron microscope (SEM) photomicrographs of detrital gold grains.(A,B) Flakey grains with rounded edges. (C)"Sandwiched" gold grain with inclusions entrapped by the bending of the gold.(D) "Sandwiched" gold grain. (E) Repeatedly bent gold grain.(F) Gold toroid with quartz inclusions (after Giusti, 1986).

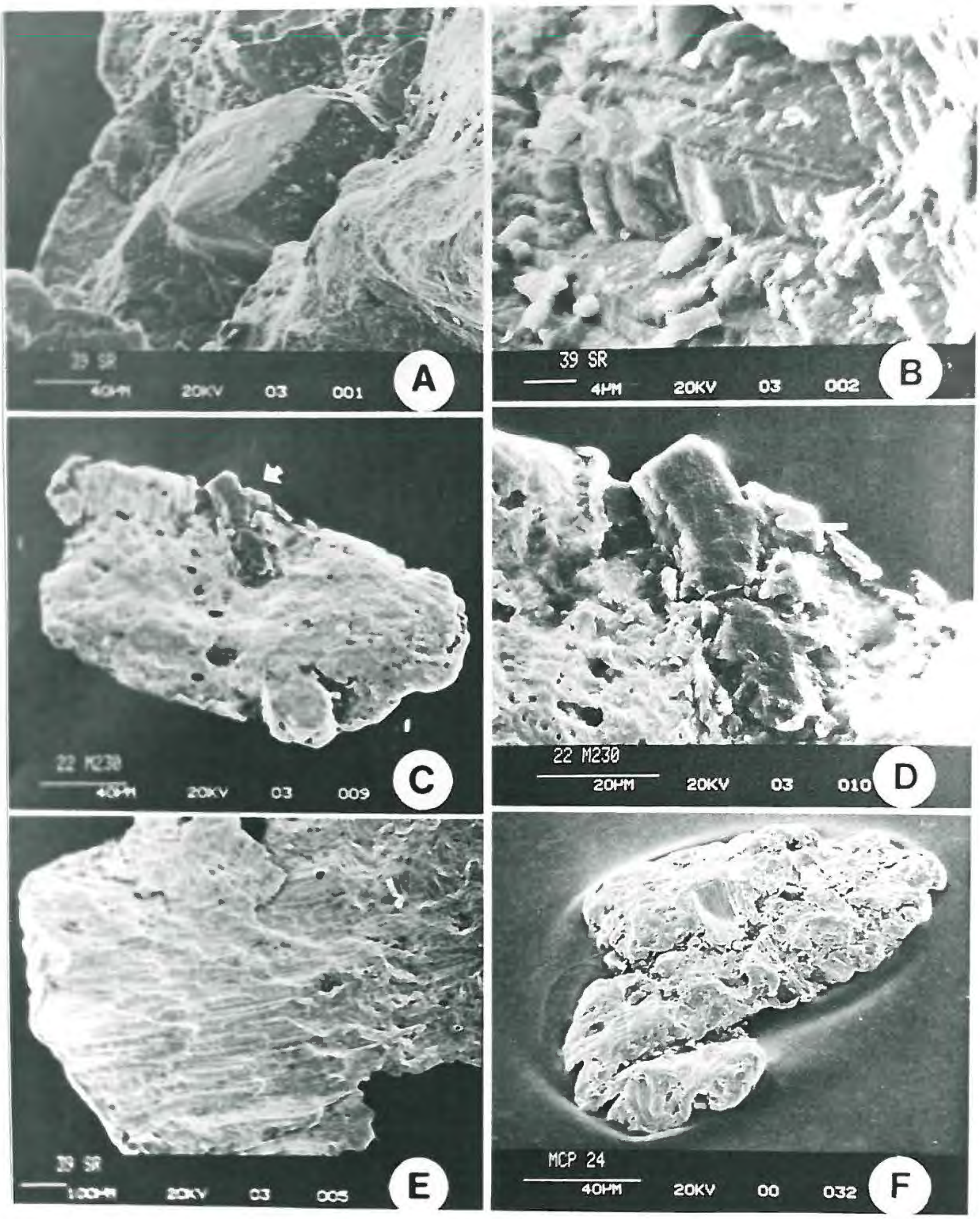


Figure 17. SEM photomicrographs of detrital gold grains.(A) Detrital gold grain with gold crystal preserved on the surface. (B) Octahedral crystal skeletons on the surface.(C) Detrital grain with rounded and bent edges with preserved crystals on its surface (white arrow).(D) Detail of gold grain in (C) showing one of the gold crystals.(E) Example of surface flow due to abrasion. (F)Gold grain showing jagged micromorphology.Scales and bent and hammered edges can be observed on the surface. A grain of quartz is embedded in the gold (white arrow), (after Giusti, 1986).

and 3) secondary, related to redeposition of "new gold" on the grains. Their genesis is still debatable, but the absence of abrasion on these grains within the placer suggests a chemical origin for the gold crystals.

All the gold grains collected from fluvial placers in Alberta by Giusti (1986) showed the presence of gold-rich rims. The rims studied were both continuous and discontinuous, and ranged from 1 to 30 microns in thickness. The rims were relatively compact, or dendritic and porous, with a lacy texture. In polished section, only 5% of the grains studied showed the typical lacy texture (Figure 18). A porous zone covering a more-compact, less-amalgamated area was also present. In the samples studied by Giusti there was no evidence of the presence of entirely secondary gold grains such as the gold spherules reported by DiLabio (1985).

Bending and consequent entrapping of originally outer portions of high-grade gold film often results in the development of high fineness cores. A new rim may subsequently form on the outer rim of the deformed gold grain (Figure 19) under the influence of mechanical and electrochemical factors. Recrystalization of the metal may occur over long periods of time at low temperatures and with a lower degree of deformation. Plastic deformation may produce flow surfaces (Figure 17E; 20 ). The original primary structure and the composition of the gold were rarely completely obliterated, essentially because gold's high malleabilty allows the metal to react to deformation by producing new surfaces. This preserves the core of the grain and also some information concerning the type of gold-bearing ore from which the placer gold was derived (Giusti, 1986). The rim of high-fineness gold will tend to be non-reactive and will protect the core of the grain from subsequent leaching (Giusti and Smith, 1984).

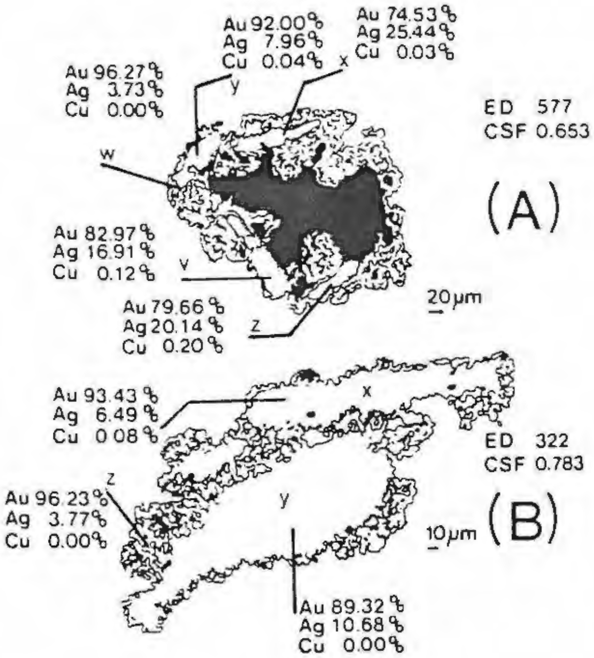


Figure 18. Sketches of polished sections of two composite gold grains. (A) Gold grain composed of four different gold particles (i.e.,X,Y,V,Z) held together by "new" high-grade gold (W).The black part of the drawing represents a vug in the central part of the composite grain. (B) Gold grain composed of two particles (i.e.,X and Y) of different average composition. The new spongy gold (Z) has the lowest Ag content (average weight percent), (after Giusti, 1986).

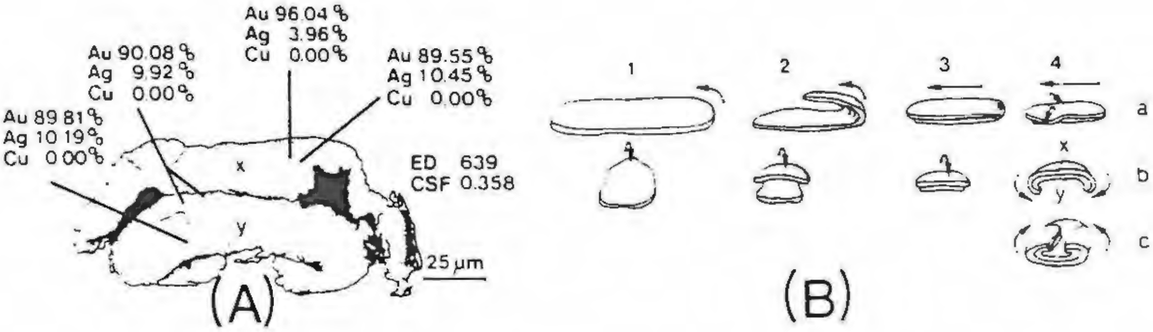


Figure 19.(A) Sketch of polished section of gold grain showing two different, consecutive generations of rims. This grain is strongly bent, and the two parts (i.e.,X and Y) have essentially the same composition except for the rim. The high-grade film around the upper surface of X has a lower Ag content than the one on its lower surface, or on the upper surface of Y, at the contact between X and Y. (B) Sequential diagram representing four major stages of the evolution of a gold particle in a placer (after Giusti,1986).

Groen et al.(1990) carried out similar studies on the gold-rich rims of placer gold grains from several localities in the south-eastern United States. Over 300 gold grains from Brush Creek, Virginia, were closely examined to identify relationships between grain morphology and factors such as character of the original lode particles, stream energetics, nature of the stream channel material, time spent in the stream, distance of transport and chemistry of the stream water. The grains were divided into five general morphological groups: irregular (41%), spherical to semi-spherical (33%), wafer-shaped with a width-to-thickness ratio <5 (14%), flake-shaped with a width-to-thickness ratio >5 (11%) and cylindrical (1%). The grains ranged in size from less than 0.01mm to 2mm; weights ranged from less than 0.01mg to 10mg. The grains were also grouped into six classes on the basis of surficial features:

1) Euhedral isometric electrum crystals on solid, fairly flat substrates of electrum ( the term electrum was used to refer to the presence of minor amounts of silver in the gold grain ). 2) Well rounded, smooth surfaces with little if any evidence of chemical attack. 3) Smoothly rounded grains with pitted surfaces. 4) Smoothly rounded surfaces with large pits containing branching-coral type features. 5) Hackly, friable-looking texture similar to that of weathered, gritty sandstone. 6) Irregular, lobate or bulbous, "stromatolite-like" texture with occasionally stepped but usually smooth individual lobe surfaces.

The general relationships between grain morphologies and surface textures were then quantified (Table 3). The most prevalent correlation existed between irregular grain morphologies and smooth, unpitted surfaces. A good correlation also appeared to exist between flake-shaped grains and lobate to hackly or grainy surface textures. An apparent relationship was observed to exist between grain size, grain shape, and distance of transport for the grains of Brush Creek.

Table 3. Correlation diagram indicating the predominance of relationships between morphologies of electrum grains and surface textures. The value in the upper-right corner of each box indicates the percentage of grains (with the particular morphology given in the top column), which possess the surface texture listed to the left. Similarly, the value in the lower left corner of each box indicates the percentage of grains (with the particular surface texture given to the left), which possess the morphology listed at the top of the column (after Groen et al.,1990).

| % of the morphological group<br>% of the surface texture group | | GRAIN MORPHOLOGIES | | | | |
|---|---|---|---|---|---|---|
| | | Irregular (~41%) | Spherical (~33%) | Cylindrical (~1%) | Wafer (~14%) | Flake (~11%) |
| SURFACE TEXTURES | Smooth unpitted (~36%) | 70-80%<br>>90% | 10-20%<br>6-10% | Insufficient data<br><2% | 3-6%<br><2% | <2%<br><2% |
| | Smooth pitted (~32%) | 15-25%<br>30-40% | 60-70%<br>55-65% | Insufficient data<br><2% | 8-12%<br>3-6% | 3-6%<br><2% |
| | Pitted with branching-coral type features (~15%) | 3-6%<br>3-6% | 10-20%<br>50-60% | insufficient data<br><2% | 30-40%<br>30-40% | 15-25%<br>3-6% |
| | Hackly to grainy (~10%) | <2%<br><2% | 3-6%<br>10-20% | insufficient data<br><2% | 30-40%<br>30-40% | 30-40%<br>45-55% |
| | Irregular lobate (~7%) | <2%<br><2% | <2%<br>8-12% | insufficient data<br><2% | 10-20%<br>25-35% | 35-45%<br>55-65% |

Near the headwaters of the creek, where a load deposit was located, irregularly shaped grains up to 1mm were observed with the average grain size being 0.2mm. Downstream (19km) the average grain size was less than 0.1mm. Grain morphologies were seen to evolve in a predictable trend, from the original irregular form through to semi-spherical and wafer-like shapes, ultimately taking up the form of flakes.

Most of the grains of placer gold from Brush Creek exhibited some degree of gold-rich rim development. The cores of the grains had a compositional range of 549 to 849 fine. Microprobe analysis of the gold-rich rim on grains showed that 95% of the rims had a composition of > 985 fine with the remaining 5% having between 967 and 985 fine. The boundary between the individual cores and rims was found to be sharp in most instances. Grains with an incomplete rim were found to have gold-rich pockets wherein the enrichment areas occur in small embayments on the grain surfaces. In other cases the rim was fully pervasive and enclosed the entire core. The pervasive rims were found to be porous. Giusti (1986) recognized similar features in gold placer grains from Alberta.

Groen et al. (1990) found that there were no gold-rich rims developed in lode gold grains from the source area, which implies that the rim formed after liberation from the host rock. The irregularly shaped placer grains, which are relatively new to the stream environment, exhibited little or no develpoment of a gold-rich rim. The flat, well worn, flake-shaped grains on the other hand, exhibited the most extensive development of a gold-rich rim. The spherical, semi-spherical, and wafer-shaped grain morphologies showed intermediate degrees of rim development. The surface features were also found to show a relationship to rim development. There was an increasing progression in the degree of rim

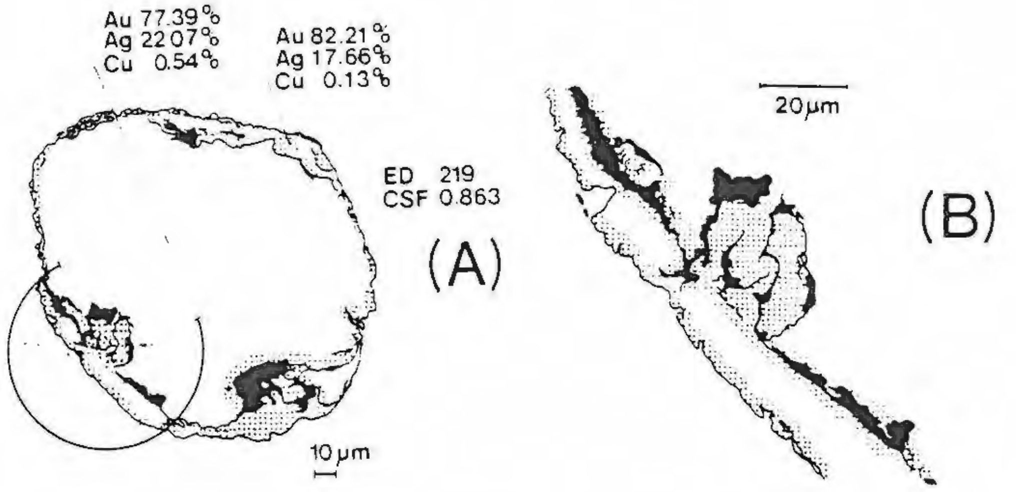


Figure 20. (A) Sketch of a gold grain from an Alberta placer (The Au, Ag, and Cu values represent average weight percent).It has a very high Corey Shape Factor(0.863), a typical gold-rich rim, and folded edges. (B) Detail of the same grain showing the complicated pattern of the gold-enriched portion of the edge of the grain, caused by repeated bending and "surface flow" (after Giusti,1986).

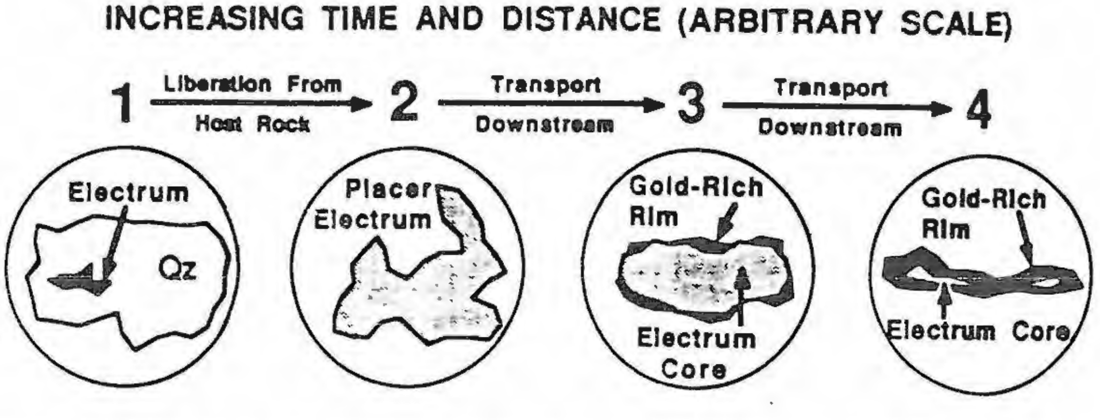


Figure 21. Schematic illustration depicting the chemical alterations experienced by grains of placer gold as they are transported downstream. The figure in each circle is representative of a sample's appearance in polished section. The following characteristics are typical of each grain's particular stage of development:(1) unrimmed gold grain in mineralized quartz vein, (2) irregularly shaped grain of placer gold with little or no evidence of gold rimming, (3) spherical to wafer- shaped grain of placer gold with spotty to intense development of gold-rich rimming, (4) flake-shaped grain of placer gold with thick, very well-developed gold-rich rim (after Groen et al. 1990).

development corresponding to the following respective surface textures: smooth, smooth pitted, pitted and branching features, irregular hackly, and lobate. The "euhedral grains on gold substrate" texture was only observed on one grain. The crystals and the substrate had fineness values of between 807 to 820. They concluded that the compositional homogeneity suggested that the crystals were most likely residual lode gold crystals, as indications suggest that the gold remobilized in the weathering environment in the study area, is precipitated as virtually pure gold.

A sequential trend exists (Figure 21) which relates the formation of the gold-rich rim to the morphology, surface texture, and distance of transport of the placer gold grain. The observed morphologies and surface textures can be roughly correlated to this trend of increasing development of a rim with time spent in the stream. This suggests that the physical characteristics of placer grains can be related to the presence and nature of a gold-rich rim. The contact between the gold-rich rim and the lower-fineness core in the grains from Brush Creek was very sharp and well defined. There was no apparent relationship between the purity of the gold-rich rim and the composition of the underlying electrum core. The gold-rich rim was seen to have formed by precipitation of gold from surrounding solutions. Simple leaching of silver from the electrum surface was seen to be an ineffective mechanism for the enrichment of gold. Diffusion of silver to the surface of a placer gold grain to expose it to oxidizing meteroric waters, followed by the creation of a diffusion-enhanced leaching process was regarded as having been far too slow to produce the natural rim thicknesses; furthermore, this mechanism fails to produce the sharp gradients in concentration observed in natural grains. Self-electrorefining of placer grains was considered to be a likely process of forming gold-rich rims and was seen to operate in tandem with dissolution-precipitation to produce the gold-rich rims.

## 2.4 Beach Placers

Beach placers can be classified according to their location, tectonic history and genesis. Boyle (1979) groups beach placers into two main classes; 1. Elevated beach and shoreline gravels and 2. Depressed beach and shoreline gravels, and further differentiates between modern and fossil beach placers. Kazakevitch (1972) regards beach placers as being a subclass of marine placers which consist of; 1. Beach placers, 2. Placers on underwater slopes, and 3. Placers in near shore still water.

Beach placers are formed by the winnowing action of waves and longshore drift along present and past shorelines bordering lakes, seas and oceans, where a source of the gold is available for concentration. The concentrating processes may be aided by tidal movements and strong winds (Reid and Frostick, 1985b; Kolesov,1974). The majority of beach placers form along rectilinear shorelines.

Gold in beach placers may be derived from; 1. the bedrock occurring along the shoreline, 2. sediments deposited by rivers and streams onto the shore, and from 3. stream and river terraces, sea terraces and gravel plains that border the coasts. The gold is fine grained and has a high fineness (900>). The fine grain size of the gold is partially due to comminution of the gold particles during transport by rivers and streams (Yeend, 1975). While a certain proportion of the gold may have been transported in solution, or as a colloid, where it was deposited on entering the marine environment (Boyle, 1979; Schmitt et al.,1993). Silver may be leached from the gold particles (Desborough, 1970), or authigenic gold may be deposited on grains (Groen et al.,1990) during transport which would account for the high fineness of the gold grains found in beach placers (Boyle, 1979).

Beach placers are generally comprised of sand, quartz and shingle clasts, the latter having been formed from the country rocks cropping out along the coastline. Clay beds and hard pans are common in raised beach placers. Accumulations of mollusk shells are frequently found to be associated with the placer deposits and are used as marker horizons.

Examples of beach placers include those found at Nome on the Seaward Peninsula of Alaska, the Oregon and California coasts, some of the Chilean beaches as well as the Westland and Southland coastlines of New Zealand.

The beach placers at Nome (Figure 22) are a classic example which highlight most of the salient features of gold-bearing beach placers. Boyle (1979) gives a general overview of the Nome beach placers while more detailed descriptions of the deposits are given by Hummel (1962a,b) and Cobb (1973).

The Nome beach placers are underlain by a bedrock of intensely foliated and faulted schists, graphitic quartzites, phyllites, limestones, graphitic slates, granites and greenstone remnants. The majority of these rocks have quartz-carbonate veins which have variable concentrations of free gold and sulphides. The gold-bearing placers of Nome are often closely associated with the auriferous schists of the Nome Group. The coastline at Nome is characterized by a cresent shaped, flat, alluvial coastal plain or tundra which is developed between the sea and the highlands. The sediments of the alluvial plain consist mainly of fine sand and clay with minor coarse gravel layers all of

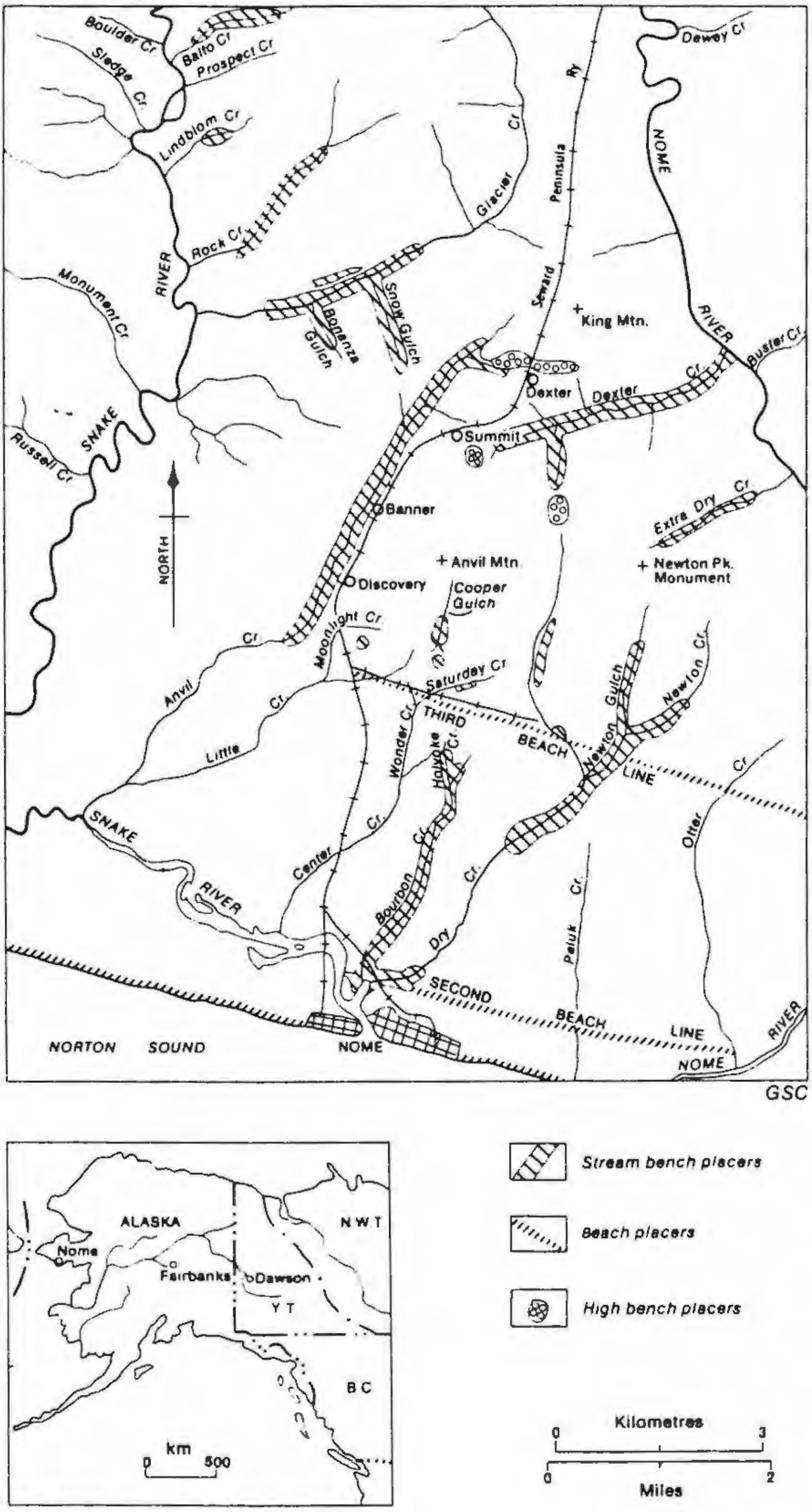


Figure 22. Map showing the location of the Nome district, Alaska and the distribution of the various types of auriferous placers (after Boyle,1979).

which are slightly auriferous. They represent deltaic deposits laid down in the sea by streams and rivers. The sediments transported and deposited by the streams and rivers were derived from the highlands which are host to numerous primary gold deposits. The gravels and sands obtain a thickness of 30m in places and are often covered by layers of clay and decayed organic matter.

Several types of placer occur in the Nome area, these include;

1. Eluvial placers,
2. Gulch, stream, creek and river placers,
3. High-bench placers which represent stream placers laid down in former drainage systems,
4. Gravel plain placers,
5. Beach placers which include modern, buried and raised types.

Studies undertaken in the Nome area have identified twelve recognizable beaches (Figure 23). The beaches represent successive periods of coastal uplift and sea level fluctuation which have taken place over a considerable length of time.

### The Modern Beach

The modern beach placers have gold occurring within bands 75m to 90m wide and 0.5m to 5.5m thick which parallel the coastline. The placers are situated some 14 m above the underlying bedrock and have the gold concentrated on clay or micaceous sandy false bottoms within the placers. The gold which is fine grained occurrs in varying amounts in discontinuous stratified lenses of sand, with clasts of schist and limestone.

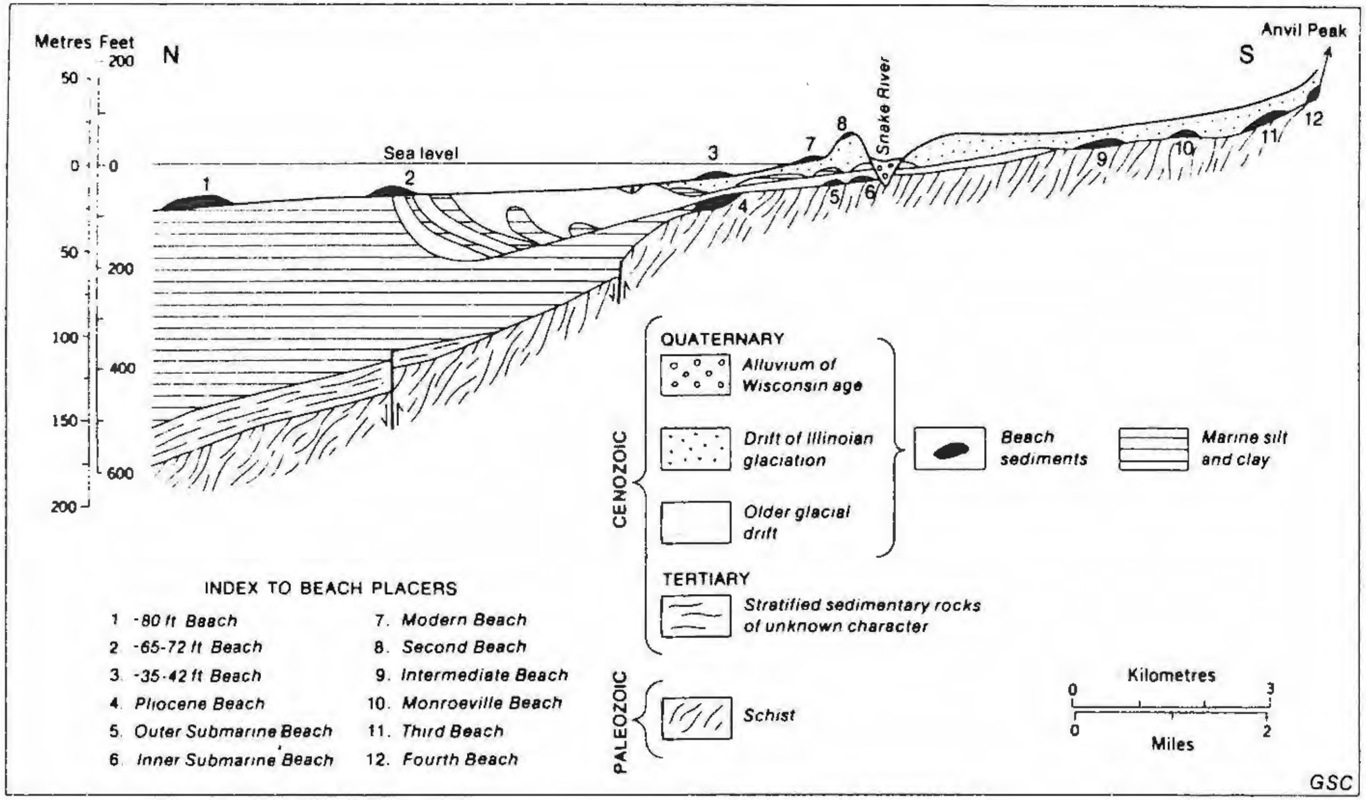


Figure 23. Geological section across the coastal plain at Nome, Alaska showing the various auriferous beaches (after Nelson and Hopkins,1972).

## The Second Beach

The second beach is developed 800m inland from the coast and is situated roughly 12 m above sea level. The gold occurrs in a zone 7.5m to 30m wide and 1.8m thick on a false bottom of sandy and micaceous sediment, which is buried under more than 4.5m of overburden. The gold is generally fine grained and flakey, with occasional large grains.

## The Submarine Beach

The submarine beach occurs almost directly under the second beach (17m below). The gold in this placer lies either on the bedrock or on false bottoms of clay, sand and gravel. The gold which is fairly coarse grained is uniformly distributed within a unit 0.3m to 1 m thick and 90 m to 120 m wide. Grades of 5,6 to 15,5g/m$^3$ were reported to have occurred in these placers.

## The Intermediate Beach

The intermediate beach is situated 2.8 km inland from the sea and rests on bedrock 6 m above sea level. The gold present is fine grained and lies on the bedrock within a zone 120 m to 180 m wide and 0.3 m to 1 m thick, (reported grades 0.5- 21g Au/m$^3$). This beach is characterized by the presence of numerous mollusk shells.

## The Monroeville Beach

The Monroeville beach is distinguished by coarser gravels and coarser gold, which occurs in shattered bedrock 10 m above sea level. The gold is concentrated in a zone 120 m to 150 m wide and 0.3 m to 1 m thick, which is overlain by 15 m of verburden.

## The Third Beach

The third beach is situated some 20 m above sea level and rests mainly on bedrock and is covered by 6 m to 36 m of overburden. The gold occurs on the bedrock in a zone 1.5 m to 3.5 m thick and 30 m to 180 m wide. The richest concentrations of gold occur in this beach placer (reported grades of up to 28g Au/$m^3$). The gold is generally fine grained with occasional coarse grains and nuggets occurring within the placer.

## The Fourth Beach

The fourth beach marks an ancient shore line which lacks any significant concentrations of placer gold.

Nelson and Hopkins (1972) have identified other beach placers in the Nome area which occur offshore and on bedrock surfaces (Figure 23). Rich concentrations of placer gold have been reported to occur offshore in coarse relict sediments. The distribution of the gold in these sediments was found to be highly complex (Nelson and Hopkins,1972;Luepke and Leong 1991).

The morphological characteristics, behaviour and chemistry of gold grains from beach and marine placers is highly diverse because of their polygenetic origin. Repeated recycling of the gold in response to eustatic changes of sea level and tectonic activity complicates the interpretation of gold grain morphology. Gold-rich porous rims are often developed on the gold grain surface. The source of the gold may be in the rocks along the shores; in sediments deposited by streams upon the coast; and in slightly auriferous stream or river terraces, sea terraces and gravel plains that border the coast. In deltaic and swamp environments the gold may occur as colloids or in olution.

## 2.5 Glacial and Fluvioglacial Placers

Glacial activity tends to destroy pre-existing placers and disperse concentrations of gold. Even so, several glacial and fluvioglacial gold placers with economic potential are exploited around the world. These occur in New Zealand, in the Andes of Peru and Bolivia, in Siberia and northern Europe, and in parts of Canada and Alaska (Stoll 1961; Boyle 1979; Matthews 1983; Herail et al. 1989; Schneider 1990).

Glacial sedimentary deposits comprise till sheets, kames, eskers, moraines, terraces, stream gravels and outwash deposits. The water-sorted materials associated with glaciers of both mountain and continental type are generally the sediments that contain economic concentrations of gold. Glaciation does not always lead to the dispersion of gold concentrations. In some instances glacial deposits have covered and prevented the subsequent erosion of pre-existing gold placer deposits.

The glacial and postglacial gold placers of the Westland and Nelson provinces of New Zealand (Figure 11, p23) have been extensively worked for their economic concentrations of gold. They serve as prime examples of glacial and fluvioglacial placer deposits (Boyle 1979; Henley and Adams 1979).In northern Westland the placers are underlain by non-auriferous Miocene marine sediments (clays with glauconite) of the Blue Bottom Formation and slightly auriferous Pliocene gravels of the Old Man Formation. These gravels ( up to 600m thick) consist of loosely consolidated well rounded pebbles of greywacke, granite and schist. The gold in the Old Man Gravels was probably partly derived from the Precambrian Greenland and Waiuta rocks, which contain auriferous lodes, and partly from the geosynclinal schists east of the active Alpine fault. Although the Old Man Gravels have only minor concentrations of gold they did provide an important source of gold in sediments, which could be reworked by younger Pleistocene and Recent placers.

The Old Man Gravels are overlain by Pleistocene moraines and glaciofluvial deposits, laid down by piedmont and valley glaciers, that descended from the Alps to the present Westland coastline. The deposits which are auriferous and of several generations (Boyle, 1979), include esker, kame, stream and outwash plain gravels and sands. The auriferous sediments comprise sands and gravels deposited below the glaciers and were winnowed from the frontal moraines. The source of the constituents of the Pleistocene gravels and sands, and the gold was probably varied, some being derived from the Precambrian Greenland and Waiuta greywackes and their auriferous lodes, some from the reworking of the older Tertiary and Cretaceous conglomerates and sands. The concentration of gold progressively decreases with distance from the ancient ice edges. The Pleistocene deposits have in some cases been reworked to yield Quarternary and Recent placers. The Westland placers discovered in 1864 have yielded in excess of 144 600 kgs of placer gold (Henley and Adams, 1979).

Herail et al. (1989) in their study of the gold particles in the glacial and fluvioglacial placers of the Ancocala-Ananea Basin in the southeastern Andes of Peru, found that 84% of the particles were smaller than 300 microns, while only 1% were larger than 1mm. The size of the gold grains was found to vary according to the type of gold-bearing sediment (Figure 24). Within the tills the gold particles are predominantly <200 microns. Along a lateral moraine the average size of the gold particles increased from upstream (130-150 microns) to downstream (300-310) by a factor of two over a distance of 10km.

The average particle size in the proximal fluvioglacial sediments was bigger, with 25% of the particles measuring between 300 and 500 microns. Downstream, in the distal fluvioglacial and fluvial deposits, the gold size distribution decreased rapidly. The least flattened gold particles were found in the upstream moraine sediments (Figure 24B) while the gold grains which had undergone the greatest amount of flattening were those from the fluvioglacial sediments (Figure 24D).

Herail et al.(1989) examined gold grains collected from the frontal moraine of the San Andres glacier which cuts through known primary gold deposits. The gold particles which had been transported 1km still exhibited primary crystal outlines. They were characterized by numerous wide and deep striation marks, crush marks and rolled-up edges. Grains of quartz were often found to be embedded in the gold particles. These features became less apparent downstream. In the fluvioglacial sediments the gold grains became more rounded and flattened exhibiting fluviatile features.

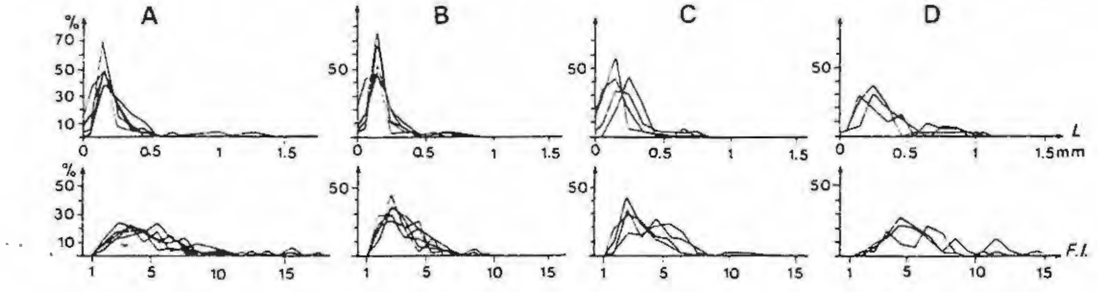


Figure 24. Gold particle size and flatness variations of the glacial and fluvioglacial deposits from the Ananea-Pampa Blanca area. (A) Moraine of the Ancocala Glaciation; B) moraine of the Chaquiminas Glaciation (upstream); (C) moraine of the Chaquiminas Glaciation (Viscachani area); (D) fluvioglacial material from Islapampa (after Herail et al 1989).

# 3 GOLD PLACER EXPLORATION

## 3.1 Target Selection

Target selection should be based on the knowledge of the occurrence and genesis of placers, taking into account the physical principals of hydrodynamics and sediment transport, as well as an understanding of sedimentary environments of deposition. On a regional scale, the location of placers will be controlled by tectonic settings, climate, geomorphic factors (time constraints, size of drainage areas and denudation rates) and gold source. Convergent plate boundaries and crustal narrowing in continental areas would provide the best environments for extensive placer formation and should be considered as potential targets. Areas of tectonic instability associated with the plate margins of the circum-Pacific are favourable target areas (Henley and Adams, 1979). Orogenic belts favour high rates of uplift and consequent erosion. Uplift leads to changes in hydraulic base level, rejuvenation of existing drainage patterns and the formation of new patterns, the production of large amounts of sediment and the reworking and redeposition of earlier sediments, all of which favour placer formation.

Targets should include areas with large drainage basins, with moderate to low denudation rates, where large volumes of rock have been eroded and deposited under weathering conditions which favour the release and deposition of gold contained in source rocks (Loen,1992). Favourable morphogenetic regions exist where placer formation is favoured (Sutherland, 1985), these include cold non-glacial regions, humid tropical areas and semi-arid to arid regions of the world (Figures 4 and 5 on page 10) and should be considered during target selection.

## 3.2 Exploration Techniques

Having selected a target area, exploration should incorporate geochemical, geophysical and remote sensing techniques.

### 3.2.1 Geochemical Methods

Geochemical methods should select sample sites which are most likely to locate concentrations of detrital gold. Water-laid placers occur in a variety of geomorphological sites and over a wide range of scales (Smith and Minter, 1980; Slingerland, 1984). Large-scale concentrations (order $10^4$m) are those which occur on regional or system-wide scales as products of long term interactions among time-averaged flow variables, available heavy minerals, and substrate characteristics. The intermediate scales (order $10^2$m) of concentrations are associated with major depositional or erosional topography within the sediment-transporting system. In fluvial settings these are bars, short channel segments and riffles etc. The small concentrations (order $10^0$m) occur at the sediment-bed scale and are represented as heavy-mineral-rich laminations in stratified sequences. Sorting associated with the formation and migration of bedforms is a dominant cause of small-scale segregations. These scales are hierarchical in that smaller scales are superimposed on larger ones. A few heavy minerals might concentrate on a small scale over a very short period of time in response to some sorting event, but increasingly larger scales of concentrations will require successively greater areas over which the sorting mechanism is applied. An example of this would be a strand-line placer (large scale) which may be dominated by patchy concentrations in the beach swash zone (intermediate scale); these concentrations in turn are composed of segregated heavy-mineral-rich laminations (small scale). Sites of heavy-mineral concentrations (Table 4) should be identified during the design of sediment sampling programmes.

Table 4. Observed sites of water-laid placers (after Slingerland and Smith, 1986).

| Sites |
|---|
| Large scale ($10^4$ m) |
| Bands parallel to depositional strike |
| Heads of wet alluvial fans |
| Points of abrupt valley widening |
| Points of exit of highland rivers onto a plain |
| Regional unconformities |
| Strand-line deposits |
| |
| Incised channelways |
| Pediment mantles |
| Intermediate scale ($10^2$ m) |
| Concave sides of channel bends |
| Convex banks of channel bends |
| Heads of midchannel bars |
| |
| Point bars with suction eddies |
| Scour holes, especially at tributary confluences |
| Inner bedrock channels and false bedrock |
| Bedrock riffles |
| Constricted channels between banks and bankward-migrating bars |
| Beach swash zones |
| |
| Small scale ($10^0$ m) |
| Scoured bases of trough cross-strata sets |
| Winnowed tops of gravel bars |
| Thin ripple-form accumulations |
| Dune crests |
| Dune foresets |
| |
| Plane parallel laminae |
| |
| Leeward side of obstacles |
| Beach berms |

### 3.2.2 Remote Sensing Techniques

Aerial photographs and Landsat imagery techniques provide a useful and cost effective means by which terraces, abandonded channels and other depositional features can be identified. Changes in vegetation growth, related to substrata changes in abandonded channels and surrounding areas can be located using multispectral imagery. The use of near infra-red wavelengths and thermal infra-red imaging can highlight changes in vegetation cover. Infrared scanning can be used to highlight buried channels, especially in areas with permafrost where the channel deposits are thawed. Channels buried to depths of 12m have been identified in this way in the Yukon area.Microwave imaging (radar) can be used in vegetated tropical terrains where cloud cover reduces the effectiveness of remote sensing techniques. Radar can be used to penetrate and provide data on sand and snow covered substrata. In arid areas, buried channels with a slightly higher moisture content may also be located using multispectral scanners.

### 3.2.3 Geophysical Methods

Geophysical methods can be used to determine the character of underlying rocks and unconsolidated material in various placer environments.

#### 3.2.3.1 Magnetometric Surveys

The application of vertical-field magnetometer measurements to the exploration and evaluation of placer deposits depends on the association of magnetic concentrations with the heavy minerals of the deposit. Magnetometric surveys are of no value in finding placers which contain insufficient magnetite, or are associated with large bedrock magnetic anomalies (Joesting 1979). Test surveys undertaken in Alaska indicate that where placer deposits contain sufficient magnetite, they can be recognised in unconsolidated sediments up to 112m deep, although, the deeper the concentration is, the more difficult it is to recognise (Anderson and Johnson, 1970). Bedrock of various magnetic intensities, variable depths to bedrock, and variable depths to the concentrations of magnetite within the unconsolidated sediments, all influence the results of magnetometric surveys.

### 3.2.3.2 Resistivity Surveys

Resistivity surveys can be used to highlight layers within sedimentary packages, giving an indication of their thicknesses and configurations. The resistivity of bedrock generally differs from that of unconsolidated deposits, so the position of bedrock can be determined. The temperature of unconsolidated deposits also affects their resistivities, especially when the temperature is below $0^{o}$ C. The high resistivities of frozen deposits prevent interpretations concerning stratification from being made, but allow determination of the extent and approximate depth of frozen deposits in areas of discontinuous permafrost (Joesting, 1979). Resistivity and other geophysical surveys can be carried out in drill holes. The cost of these surveys is low when compared to drilling costs.

### 3.2.3.3 Gravity Surveys

Gravity surveys can be used to indicate the general location and configuration of channels in bedrock. The presence of ice lenses, and unnoted changes in bedrock elevation, can seriously affect the results of gravity surveys. Gravity surveys are best used as a reconnaissance tool prior to seismic surveys.

### 3.2.3.4 Seismic Surveys

Seismic surveys may be used to characterise layers within unconsolidated deposits. If conditions are ideal, the layers, their thicknesses, and the depth to bedrock may be determined. Down borehole vertical seismic profiling has also been used successfully to characterise unconsolidated strata. Seismic responses vary depending on the temperature and the water content of the material being surveyed. They are also affected by the presence of ice lenses. These factors can seriously hamper the interpretation of the results of surveys of shallow unconsolidated deposits.

## 3.3 Evaluation

Evaluation of the placer should be undertaken once the general shape and extent of the deposit has been determined. A variety of sampling methods can be used to evaluate placer deposits. Where possible, geological mapping of the placers should be undertaken to establish the distribution of the potential gold bearing horizons, and to determine whether there are frozen zones, calcrete layers, clay and silt units, uneven bedrock surfaces and large boulders, which might affect mining methods used in processing sediments. Interpretation of the history of deposition and preservation of the deposits should be undertaken. Stable isotope dating and palyology can be used to determine the age of placer units within the deposit.

When evaluating regions which have been mined previously, care should be taken to outline those areas which have been worked.

Bulk samples should be taken to determine the gold content of the deposits. Samples should be taken in such a way that the gold content of specific horizons can be determined. A distinction should be made between mineralized and barren horizons. Samples can be collected from pits, trenches, shafts or from large diameter drill holes. Large mechanically-dug excavations are cost effective and fairly easy to map and sample. The volume and mass of the samples should be determined and the heavy minerals concentrated by chemical or mechanical means, depending on the expected character of the gold. Giusti (1986) characterized the gold particles from different placers and determined the most effective means by which the gold from these placers could be concentrated (Table 5).

The volume of the samples is measured and the heavy minerals separated by various means (sluicing, riffling, jiggers and chemical floatation methods). The grade of the placer deposit is then expressed as a value per unit volume.

Where deposits are shallow, trenching is the most accurate and cost effective means of evaluating the placer (Vlasov and Zhelnin, 1964). In addition to being more accurate, trenching enables the margins of the valuable mineral-bearing zones to be identified. Trenching methods have located economic concentrations of gold which have previously been written off by pitting methods. Trenches can be spaced 25% further apart, than rows of test pits without a significant loss in accuracy or information (Vlasov and Zhelnin, 1964). Pits and trenches should be arranged to sample sections across the length of the placer deposits. Visual inspection of the walls of pits and trenches can be done to determine the character of grain sizes of the gravel or alluvium present. In addition, gold bearing and barren sections of the deposits may sometimes be found by simple inspection and panning of samples taken from the trench walls. Trenching enables the depth to bedrock to be determined and exposed for inspection and sampling.

Table 5. Model relating placer gold characteristics to environment and the best recovery methods (after Giusti, 1986).

|  | (Increasing distance from source) → |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  | Eluvial placer | Alluvial placer |  |  |  | Delta, swamps, sea |
| Gold grain morphology | Irregular; primary crystals still preserved; lots of inclusions; very high CSF | Irregular, rounded protuberances; some primary crystals still preserved, often in cavities or folded portions of the metal; mainly inclusions of quartz; high CSF | Flaky, jagged surface, rounded outline; recrystallized; plastic deformation; medium–small CSF | Flaky, rounded, multiple bending; recrystallized; some secondary octahedral crystals on the surface; high CSF | Rounded, often porous; small ED; high – very high CSF | Gold as colloids or in solution; trapped by organic matter |
| Rim effect | Porous rim is frequent | Porous to compact | Compact | Compact | Compact to porous | Porous variety is frequent |
| Abrasion | Moderate | Strong | Strong | Strong | Moderate | Minor |
| Chemical weathering | Very strong | Moderate – minor | Minor | Minor | Minor | Moderate |
| Most representative mesh size | +35 | −35 to +120 | −120 to +200 | −120 to +200 | −200 to −400 | −200 to −400 |
| Prevalent sediment type | Cobbles, pebbles | Pebbles, sand | Sand | Sand, silt | Silt, sand | Silt, clay |
| Environment | High energy | High – medium energy |  | Medium – low energy | Low energy | Low energy |
| Suggested recovery methods | Mechanical (panning, sluicing, jigging, rocking) | Mechanical and chemicial (sluicing, tabling, flotation) | Chemical and mechanical | Chemical and mechanical | Chemical and mechanical | Chemical |

[a] The model assumes (1) monocyclic gold and (2) relatively coarse grained gold at the source.

In many cases, the results obtained from a few days of trenching will determine if further exploration is warranted.

Drill sampling should be undertaken in deep, wet, or frozen deposits, where sampling by pits and trenches is not practical. Various drills offer a range of pit and core sizes, depth capabilities, drilling rates, and sample recovery methods. A considerable amount of time can be saved by using drilling techniques to evaluate potentially large auriferous deposits.

Drills commonly used in placer gold sampling programmes include: churn drills, down-the-hammer drills, hammer and centre sampling rotary drills, and clam type drills (Colp, 1983).

Up until 1980, practically all placer drilling was accomplished with churn drills (Figure 25) of the type developed for drilling water wells. The overall operation of sampling placer ground with churn drills envolves
a) the driving of casing into the ground,
b) drilling and breaking up the material,
c) adding water to make a sludge that is pumped out of the hole. The sludge and cuttings are then processed and the gold concentrated by mechanical and\or chemical means. Values and grades are then calculated for specific volumes of material sampled. Drawbacks include contamination of samples when drilling and pumping are carried out below the casing. Large rocks can hamper drilling as can tightly consolidated ground and large volumes of ground water.

Down-the-hole hammer drills are pneumatically operated bottom-hole drills, that efficiently combine the percussive action of cable tool drilling with the rotary action of rotary drilling. They are used for fast and economical drilling of

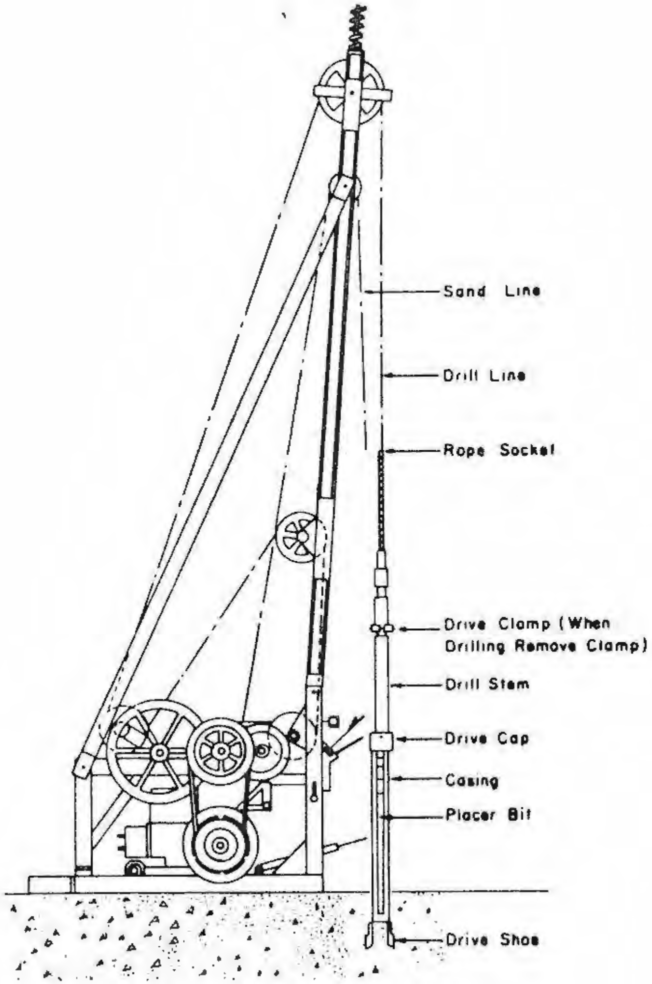


Figure 25. Basic equipment used in churn drilling (after Colp, 1983).

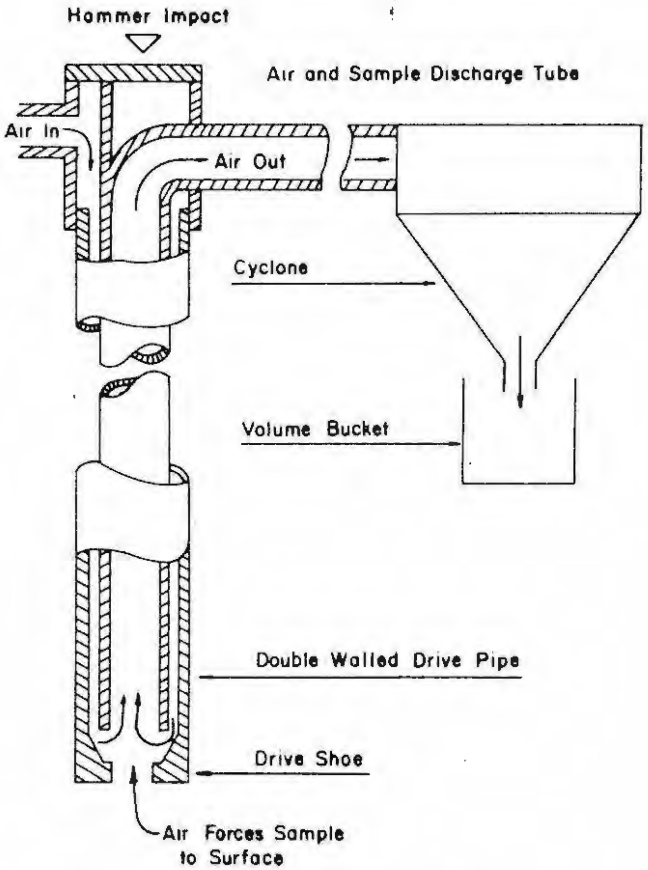


Figure 26. Driving head, bit, and sample return system (after Colp, 1983).

medium-hard to hard formations in placer gravel sampling. The compressed air drives the hammer at the bottom of the hole and forces the cuttings from the hole via an air and sample discharge tube into a cyclone and volume bucket. Holes are generally straight, and boulders less problematic. Casing is not always required as the air and\or water is injected down the drill tool and out the bit. The cuttings come up the annulus between the tools and the hole diameter. However, during placer sampling this drilling method should not be used without casing as particles of gold stick to the rough sides of the drilled hole. The casing must follow as close behind the bit as possible. In this way, air and\or water forced down the drill pipe will bring all the cuttings to the surface. They will then enter a casing discharge tube which discharges into a cyclone. The cyclone receiving the cuttings discharges its samples into containers, after which measurements are made.

Diesel hammer and center sampling rotary drills (Figure 26) discharge their drill cuttings by reverse circulation, opposite to the bottom hole hammer drill just described. The diesel hammer drill consists of a double wall pipe which is driven down by a diesel-operated pipe hammer. Air and\or water under pressure is forced down the annulus of the drive pipe. Material cut by the drill bit is transported to the surface through the inside of the pipe by the drilling medium. Discharged material is accumulated in containers as it emerges from the cyclone which allows collection of samples at specific intervals. The centre of the drive pipe is always clear and the bit always remains at the bottom of the hole which limits contamination.

Clam type drills are capable of drilling holes 91cm in diameter to depths of 30 m or more depending on the nature of the ground. The drilling unit uses a clamshell type excavating tool to dig the material from the confines of 91cm casing which is driven into the placer material. This provides larger samples and better classification of sample material. The larger the drill hole the more representative will be the sample of the placer deposit. A balance must be achieved between evaluation requirements and the cost of drilling larger holes.

Careful planning and the use of geostatistics should be used to choose optimum spacing and location of drill holes. The effectiveness of previous evaluation programmes of similar placer deposits should also be considered and used in planning drilling programs.

When dredges are used for mining placer deposits a precise comparison can be made between estimated and actual grades of the deposit (Hester, 1970). Low-grade deposits tend to be undervaluated and high-grade deposits overvaluated. This is because boreholes are often too widely spaced to disclose the many rapid variations in gold distribution. The coarser gold particles are too erratically distributed to have been assessed properly by the drilling programme. It is the coarse gold which is responsible for the variations observed between values indicated by drilling, and those actually recovered by mining. Historical experience and geological interpretation should contribute to the reduction of these variations.

Once evaluated, a decision can be made on how or whether the placer deposit is to be mined. Mining methods will be based upon the characteristics of the deposit to be mined and the scale of the mining operation. Logistical factors such as availability of water, access, presence of permafrost and environmental issues (which should be considered at an early stage during target selection) will also affect the viability of exploiting the placer deposit.

## CONCLUSIONS

Surficial gold deposits have been, and will cotinue to be, an important source of gold. Spiralling costs in the gold mining industry, and the increased demand for gold, make surficial gold placers an economically attractive type of deposit, towards which exploration efforts should be directed.

In order to locate additional surficial placer deposits, an understanding of their genesis, where they are likely to be formed, and the controls which affect their distribution, is essentiial. Insight into these processes has been gained from the detailed study of similar placer deposits.

The development and distribution of surficial placer deposits is strongly controlled by tectonic setting. Convergent plate boundaries and crustal narrowing in continental areas provide a suitable environment for the formation of gold placers. Regional uplift has resulted in erosion and reworking of rocks and sediments containing gold, followed by deposition, concentration and preservation in suitable sedimentary environments. The distribution of placers is also largely a product of variation in geomorphological processes acting at the earths surface. Climate controls many of the variables that are relevant to placer formation. These include weathering, denudation rates, nature of sediment supply and the potential for sediment reworking. The effectiveness of weathering processes will determine how much gold is released from source rocks and made available for later concentration in placer deposits. Several climatic/morphogenetic regions can be identified where geomorphological conditions favour placer development. Global changes in climate and accompanying changes in surface processes have provided suitable conditions for the formation of placers.

Prerequisites for the formation and concentration of large amounts of gold in placers are large drainage basins that have been eroded for long periods of time at relatively high denudation rates. Rich source rocks are not always a prerequisite for the development of surficial gold placers, although in some instances there is a direct relationship between gold rich source rocks and placer deposits.

Gold placers are surficial mineral deposits formed by the mechanical and chemical concentration of gold from weathered material by gravity, water, ice and wind to form eluvial, fluvial, marine, glacial and fluvioglacial placers. The gold is deposited and concentrated by various means in the different placers. The gold grains from these placers have distinctive morphologies and chemistries, which reflect the manner in which the gold was transported and deposited, and the chemical changes that took place during these events.

Exploration for surficial gold placers should be based on a model which identifies where these deposits are likely to occur and in what form. Exploration should incorporate geochemical, geophysical, remote sensing and geological mapping techniques.

Having identified a potential deposit, it should be evaluated using techniques which were successfully applied to other similar deposits. Gold grades can be determined by trench sampling and various drilling methods depending on depth constraints. Once the deposit has been evaluated, feasibility studies can be undertaken to determine if mining the deposit is a viable and economic proposition.

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